UNIVERSIDADE DO PORTO FACULDADE DE DESPORTO

CENTRO DE INVESTIGAÇÃO FORMAÇÃO INOVAÇÃO E INTERVENÇÃO EM DESPORTO CIFI2D

UNIVERSITY OF PORTO

Faculty of Sport

Centre of Research, Education,

Innovation and Intervention in Sport

Integrated analysis of the inter-arm coordination in aquatic locomotion

Academic dissertation submitted with the purpose of obtaining a doctoral degree in Sports Sciences according to the Decree-Law 74/2006 from March 24th.

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Porto, 2016

Silva, A. F. (2016). Integrated analysis of the inter-arm coordination in aquatic locomotion. Doctoral Thesis in Sport Sciences. Centre of Research, Education, Innovation and Intervention in Sport. Faculty of Sport, University of Porto.

KEY WORDS: MOTOR CONTROL, COORDINATION, SWIMMING, FRONT CRAWL, YOUNG SWIMMERS.

Funding

This Doctoral Thesis was supported by the Portuguese Science and Technology Foundation (FCT) grants SFRH/BD/87780/2012.

Acknowledgments

To my supervisor Prof. Dr. Ricardo Fernandes for the patience and for the constant stimulus to fulfil this goal.

To Prof. Dr. Pedro Figueiredo for his patience, constant exigency, but simultaneously helping, and above all, for his friendship.

To Prof. Dr. Ludovic Seifert for received me so kindly in his office in France and for sharing his knowledge.

To Prof. Dr. João Paulo Vilas Boas for the support through my academic career and his valuable help.

To Prof. Dr. Arturo Abraldes for his helping and companionship.

To Prof. Drª. Susana Soares that accompany me along this journey and for shared with me her office.

To Drª. Teresa Marinho for her friendship and for helping to improve my English competencies.

To all swimmers that participated in the studies, without whom it would be impossible to achieve this goal.

To coaches and directors that allowed me to be included in their teams and showed confidence in my work.

To my colleagues and technicians that helped me in this journey, especially in my data collections, namely Sara Morais, Ana Sousa, Ana Querido, 'Paulinho', Marina Sardinha, Valdir Ramos, Siwa, Dária, Ricardo, Rodrigo, Tânia Soares, Pooya, Andreia Flores, Pedro Fonseca, Márcio, Lucimere, Toni and César.

To my friends “La Famiglia”, for the days that I could not be with them.

To my brother in law, for his valuable helping, especially in my data collections.

To Cátia, Flora and Filipa, my true friends for their support and for constantly encouraged me.

To those true friendships that the PhD allowed me to strengthened, namely Renata Willig and Marisa Sousa.

To João for his valuable helping in academic issues, but essentially in emotional support.

To my nice Lara, for being my inspiration.

To my parents and my sister, for being my support and my idols, to whom I dedicate all my achieved goals.

This Doctoral Thesis is based on the following scientific papers, which are referred in the text by their Arabic and Roman numerals, respectively:

1. Silva, A. F., Seifert, L., Fernandes, R., Figueiredo, P. (2017). Coordination in front crawl swimming: A Review. Submitted for publication to **Motor Control**,

2. Silva, A. F., Figueiredo, P., Morais, S., Vilas Boas, J. P., Fernandes, R., Seifert, L. (2017). Task constraints and coordination flexibility in young athletes. Submitted for publication to **Research Quaterly for Exercise and Sport**.

3. Silva, A. F., Figueiredo, P., Seifert, L., Fernandes, R. J. (2016). Control parameter determination when manipulating task constraints. In: K.J. Słomka, G. Juras (eds.), **Current Research in Motor Control V**, pp. 246-251. The Jerzy Kukuczka Academy of Physical Education in Katowice, Wisla, Poland.

4. Silva, A.F., Seifert, L., Sousa, M., Willig, R., Alves, F., Vilas-Boas, J.P., Fernandes, R., Figueiredo. P. (2014). A multi-analysis of performance in 13- to 15-year- old swimmers: a pilot study. In: B. Mason (edt.), Book of proceedings of the **XII International Symposium on Biomechanics and Medicine in Swimming**. pp 242-248. Canberra, Australia.

5. Silva, A. F., Figueiredo, P., Ribeiro, J. Vilas Boas, J. P., Seifert, L., Fernandes, R. (2017). Integrated analysis of young swimmers sprint performance. Submitted for publication to **European Journal of Sports Science**.

6. Silva, A. F., Figueiredo, P., Fernandes, R., Seifert, L. (2017). The effect of a coordinative swimming training in young swimmers' performance. Submitted for publication to **Journal of Motor Behavior**.

7. Silva, A. F., Figueiredo, P., Ribeiro, J., Seifert, L., Fernandes, R. (2017). Are functional coordination and performance influenced by strength trainings? Submitted for publication to **International Journal of Sports Physiology and Performance**.

Table of Contents

Index of Figures

(respectively) and ϕ means that an interaction time x group effect was found with control group.

Index of Tables

Index of Equations

Abstract

Following the ecological dynamics, the capacity to adapt movements to dynamic interacting constraints of a performance environment, to achieve specific intentions and make decisions, broadly defines expertise. The purpose of this thesis were twofold: (i) to investigate which are the variables that most influence front crawl swimming coordination and understand its effects on flexibility when manipulating task constraints; and (ii) examine the effect of different coordinative and strength trainings on front crawl coordination and performance in young swimmers. The protocol contained two distinct protocols: (i) 15 x 50 m front crawl (with 5 min interval), five trials at each 100, 90 and 70% of their 50 m maximal swimming speed, randomly at 90, 95, 100, 105 and 110% of their preferred stroke frequency; and (ii) swimmers were assessed for anthropometry and flexibility and performed 30 s maximal effort on tethered swimming, 12 x 25 m on MAD-system and 50 m maximal front crawl bout. Seven aerial and six underwater cameras were used to assess kinematics, with upper limb coordination computed through continuous relative phase (allowing extracting the relative times spent in in-phase, anti-phase and out-of-phase) and index of coordination methodologies. Results pointed out that speed and stroke frequency were the main control parameters, with speed exerting a greater influence. Their manipulation showed that not all the variability is functional, i.e., the patterns nature and appropriately shifting between them seem more important than attain the highest number of changings or pattern. Performance in 50 m seems to vary more with swimmers sex rather than skill level at these ages, with specific training (same environment: the coordinative and the in-water strength trainings) exerting more changes in coordinative variables and the dry-land strength training exerting a greater influence on performance.

Key words: Front crawl, coordination, performance, young swimmers, biomechanics.

Resumo

Segundo a teoria da abordagem ecológica, a capacidade de adaptar os movimentos às restrições de interacção dinâmica de um ambiente de prova, para atingir intenções específicas e de tomar decisões, define amplamente a *expertise*. Os objetivos desta tese foram: (i) investigar quais são as variáveis que mais influenciam a coordenação em natação na técnica de crol e compreender os seus efeitos sobre a flexibilidade, durant a manipulação de constrangimentos da tarefa; e (ii) analisar o efeito de diferentes treinos específicos de coordenação e força na coordenação de nado e rendimento na técnica de crol em jovens nadadores. O protocolo foi composto por dois protocolos distintos: (i) 15 x 50 m na técnica de crol (com intervalo de 5 min) com cinco repetições em cada 100, 90 e 70% da sua velocidade máxima aos 50 m, aleatoriamente a 90, 95, 100, 105 e 110% da sua frequência de nado preferida; e (ii) os nadadores foram avaliados quanto à sua antropometria e flexibilidade e realizaram 30 s máximos em nado amarrado, 12 x 25 m no *MAD-system* e 50 m máximos na técnica de crol. Foram utilizadas sete câmeras aéreas e seis sub-aquáticas para avaliar a cinemática, com coordenação dos membros superiores calculada através de duas metodologias: a fase relativa contínua (permitindo extrair os tempos relativos dispendido em em-fase, anti-fase e fora-de-fase) e o índice de coordenação. Os resultados indicaram que a velocidade e a frequência de ciclo foram os principais parametros de controlo, com a velocidade a exercer uma maior influência. Através da manipulação destes parâmetros verificou-se que nem toda a variabilidade é funcional, isto é, a natureza dos padrões e uma apropriada alteração entre padrões parecem ser mais importantes do que atingir o maior número de mudanças de padrões motores. O rendimento nos 50 m parece variar mais com o gênero do nadador do que com o nível de habilidade nestas idades, onde os treinos específicos (o mesmo meio ambiente: o treino de coordenação e de força na água) exercendo mais alterações nas variáveis coordenativas e o treino de força no ginásio a exer maior influência no rendimento.

Palavras-chave: Crol, coordenação, rendimento, nadadores jovens, biomecanica.

List of Abbreviations

ANOVA	Analysis of variance
cm	centimeters
CRP	Continuous relative phase
D	Hydrodynamic drag force
e_p	Propelling efficiency
F	F-statistics
FI	Fatigue index
F_{max}	Maximal force
F_{mean}	Mean force
F_{min}	Minimun force
Hz	Hertz
IdC	Index of coordination
IVV	Intra-cyclic velocity variations
kg	Kilograms
m	meters
MAD-system	Measuring active drag
MANOVA	Multiple analysis of variance
MLR	Multiple linear regression
n	Number of subjects
P_o	Machanical power output
R^2	Determination coefficient
s	seconds
SD	Standard deviation
SD CRP	Standard deviation of continuous relative phase
SI	Stroke index
SL	Stroke length
SF	Stroke Frequency
SPSS	Statistical package for the social sciences
3D	Three-dimentional

Chapter 1. General Introduction

To successfully perform a wide variety of motor skills, muscles and joints should be coordinated to function together. However, the way our body decides to request some over others remains doubtful. The search for that mechanisms started with Bernstein (1967), who dedicated his career to develop the analysis upon the degrees of freedom problem, traditionally defined as the number of axes that a joint can perform (Enoka, 2008; Li, 2013). This perspective of movement control focused mainly on biomechanics, which led other theories to emerge trying to explain coordination and motor control from different points of view. However, the harnessing of the redundant degrees of freedom still remains seen as the central problem in movement coordination and control.

Kugler, Kelso, and Turvey (1980) have defined coordination as a group of muscles that often extends over several joints forcing them to act as a functional unit to achieve a goal. Haken (1983) introduced the synergetic concept that deals with systems composed of many subsystems that could be of different nature, such as atoms, molecules, cells, neurons, organs, animals and even humans, where coherent structures may spontaneously be formed by self-organization. For this author, coordination comprehends also the coherence or the regulation pattern of movement systems that can be determined according to their spatiotemporal evolution during the execution of functional activities (Haken, 1996). Newell (1996) has defined coordination as the function that constrains the possible degrees of freedom into a behavioural unit, suggesting that it implies a “bringing into relation” of the parts of the system. Those definitions highlighted that it could be possible to describe coordination macroscopically, among persons or parts of a system (body segments, muscles or cells), and also microscopically, concerning configurations of tensile states or the patterning of cellular and vascular activities (Turvey, 1990). Hence, it was also considered the goal, i.e., coordination is requested to achieve a certain target (or performance), as a functional organization of multiple degrees of freedom available to interacting parts and processes in space and time (Kelso, 2009).

The intrinsic dynamics of each individual is unique and it is shaped by three main constraints (Newell, 1986): (i) organismic, associated with the individual features (height, arm span and gender); (ii) environmental, related to the surrounding characteristics (light, temperature or humidity); and (iii) task, including rules and the goal of the movement to be performed. Through this viewpoint, when components, variables, joints or muscles are connected with constraints in a certain way, the problem of degrees of freedom reduces dramatically (Li, 2013). Therefore, and based on dynamic and ecological approaches, coordination is a dynamic process, aiming to understand the laws, principles and mechanisms that govern how behaviour evolves itself in space and time, how they are maintained and change, and how they are reorganized in an adaptive way (Jantzen & Kelso, 2015; Kelso, 1995; Kelso, 2012).

As a result of the individual's constraints management, due to the different intrinsic dynamics, various functional coordination patterns could be found for the same goal. In fact, these have been observed between and within individuals' performance variations, even in cyclic sports, confirming that they should not be considered as noise (Davids, Bennett, & Newell, 2006). Thus, they play an important role in skill acquisition (Starkes & Allard, 1993) and in supporting the exploratory behaviours when seeking and establishing functional movement solutions (Davids, Araújo, Hristovski, Passos, & Chow, 2012). Consequently, challenging individuals to perform different skill variations can be beneficial, since learners can search for functional movement solutions by adding movement variability to a target skill (Davids et al., 2012). Indeed, if more functional movement patterns arise, performers will be helped to discover and explore those functional movement patterns, showing flexibility (Davids et al., 2012), denoting that behaviour is not stereotyped and rigid but flexible and adaptive (Seifert, Komar, Crettenand, & Millet, 2014).

In fact, there is a tendency to associate consistency to expert skill performance, especially when a kinematic analysis is conducted (Ericsson, Krampe, & Tesch-Römer, 1993). However, both stability (i.e. robustness of motor functions undergoing internal and external disturbances) and flexibility (i.e. functional variability to adapt to a set of constraints) are essential to skilled performance, reflecting adaptability (Davids, Glazier, Araújo, & Bartlett, 2003; Warren, 2006). This latter refers to adapted (i.e. adapted behavior to a set of constraints revealing stability against perturbations) and adaptive (i.e. reflecting flexibility to guarantee functional solution to constraints that dynamically interact) behaviors (Seifert, Komar, Araújo, & Davids, 2016). Following this, expertise should be rather conceived as an appropriate control of variability to adapt movements to the complex and often unexpected task-specific constraints that characterise sports skills (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013). Consequently, no ideal motor coordination solution towards which all learners should aspire exists, but functional coordination patterns that emerge from interacting constraints (Glazier & Davids, 2009; Newell, 1986).

Hence, to perceive the movement mechanisms seems to be decisive in the young athletes' learning process, who are, simultaneously, exploiting different changes in their bodies. Indeed, the maturation process greatly modifies the organismic features that novices have to learn to deal with, finishing (or ending near) at 13/14 years of age, meaning that, the growth spurt has already occurred. This last phenomenon includes the peak of height velocity, which determines the development time of body dimensions, weight, strength, aerobic power and motor performance (Malina, Bouchard, & Bar-Or, 2004). Therefore, it seems that during the maturation stage, swimmers have to calibrate some technical features associated with motor control aspects. In perception and action, calibration and recalibration are necessary to establish and update the mapping between the sub-systems in which the relevant properties of the environment are perceived (e.g. visual or proprioceptive), and the sub-systems in which the action is realized (Araújo & Davids, 2011).

An entirely different environment, with specific features to be considered, is met when analysing swimming, leading practitioners to challenge their capability to adapt constantly. The maximal speed attained when swimming is ~2 $m \cdot s^{-1}$, representing only ~16% of the maximum achieved on land (Toussaint & Truijens, 2005), as water naturally imposes forward resistance (Toussaint et al., 1988), requiring propulsive forces to overcome the rising resistance with increasing speed (Berger, Hollander, & De Groot, 1999). Regarding front crawl, the fastest swimming technique and the one with a greater range of races, it was observed that 85% of the total propulsion is provided by upper limbs (Bucher, 1975; Toussaint, 1992), with their synchronization and rhythm playing an important role. In fact, coordination is related to the upper-limb organization, particularly the transition between the under and above water movements, and the time spent in propulsive and non-propulsive phases (Seifert, 2010). However, different swimmers can apply the same force and/or provide the same power output without exhibiting the same upper-limb coordination (Seifert, 2010), with the latter symbolizing one of the most fundamental, but least understood, ability of living things (Jantzen & Kelso, 2015).

The current Chapter – General Introduction – contextualises the theoretical assumptions regarding coordination, especially in cyclic movements as front crawl swimming. Chapters 2 to 8 present the experimental accomplishments of the current Doctoral Thesis. Chapter 9 introduces a general discussion among data obtained from our experimental studies with the specialized literature. Chapters 10, 11 and 12, respectively, present the key findings, suggestions for future research and references.

Swimming studies are challenging tasks as the aquatic environment represents a huge constraint since the water resistance is much higher than the air, the breathing action and the sensory information are limited by the environment, and the body is at the horizontal position. Maybe due to those characteristics, not all the existing methods to analyse coordination were used in this environment, and few studies have been conducted when comparing to land (as in running or cycling). Hence, its characteristics led to the rise of a new specific tool to measure coordination on swimming, the Index of Coordination (IdC), firstly described by Chollet, Chalies, and Chatard (2000).

In the last decade, several studies explored this tool, but mostly analysing the interaction with only one or more biomechanical (Schnitzler, Brazier, Button, Seifert, & Chollet, 2011; Seifert & Chollet, 2010) or physiological variables (e.g. Alberty, Sidney, Pelayo, & Toussaint, 2009; Figueiredo, Morais, Vilas-Boas, & Fernandes, 2013), gender (e.g. Chollet et al., 2000; Seifert, Boulesteix, & Chollet, 2004), skill level (e.g. Chollet et al., 2000; Seifert, Leblanc, Chollet, & Delignieres, 2010) and maturational stage differences (Silva et al., 2012). Therefore, in **Chapter 2**, a literature review was carried out including all studies conducted on front crawl swimming coordination. This swimming technique is the most studied regarding coordination, to enable a better analysis of the methods used and to understand how biomechanical and physiological variables interact with swimming coordination and how gender, skill level, and maturation stage limit the adopted coordination mode.

Literature review has shown that speed and stroke frequency (SF) were considered the main influencing variables that led coordination mode to change (e.g. Chollet et al., 2000; Potdevin, Bril, Sidney, & Pelayo, 2006). As all those studies were carried out in adult swimmers, a constraint manipulation was conducted, aiming a better understanding of how these variables influence the adoption of a front crawl coordination mode in young swimmers. Hence, beyond the analysis of swimmers capacity to adapt (i.e. functional variability), it was aimed to observe if flexibility existed in young swimmers' patterns (**Chapter 3**). In fact, this type of approach has been underexplored in swimming, especially with age group swimmers, who are still in the learning process. In fact, although the movement variability is known to follow the central nervous system development (Boyer, Silvernail, & Hamill, 2016; Denckla, 1974), with age, performance is related to a better ability to organize sensorimotor system to match task demands, rather than reductions in the system noise (Deutsch & Newell, 2001). It was expected that some subjects might exhibit more upper-limb coordination patterns, associated with a larger SF and speed repertoire, indicating that young swimmers should train around their preferred SF to enlarge their behavioural repertoire and, more broadly, their behavioural flexibility.

After verifying changes in motor behaviour through the manipulation of the above variables, it was assumed that speed and SF are front crawl control parameters, as they could be capable of inducing changes in behaviour (Fuchs & Kelso, 2009). However, as speed results in the product between stroke length (SL) and SF, being this latter directly related to speed, the doubt if SF or speed is the real control parameter, or even if it is the combination of both, remains. Moreover, the IdC was found to be positively correlated to speed and, consequently, to SF. Thus, in **Chapter 4**, an analysis has been conducted aiming to understand the influence of these two variables alone, or if it is the interaction between them that controls the system.

Expertise has traditionally been associated with the athletes' capacity of producing a specific coordination pattern, reducing attention demands during performance in cyclic activities by increasing movement automaticity (Ericsson, 2008). However, the recent evidence has shown that perceiving the nature of each individual intrinsic dynamics is, in fact, the central concern to understand how expert performance develops in sport (Phillips, Davids, Renshaw, & Portus, 2012). Therefore, focusing on a better insight of swimming sprint performance, a pilot study was conducted (**Chapter 5**) including a coordinative analysis and variables considered fundamental on swimming performance, namely shoulder flexibility (Saavedra, Escalante, & Rodriguez, 2010), anthropometrics (Figueiredo, Silva, Sampaio, Vilas-Boas, & Fernandes, 2015), biomechanics (Laett et al., 2010) and strength (Morouço, Marinho, Amaro, Pérez-Turpin, & Marques, 2012). In this study two different skill level groups have been included, both comprising young female swimmers, thus avoiding gender constraint.

During the maturational process, several differences occur in swimmers' body and their capabilities leading to a clear gender distinction (Kojima, Jamison, & Stager, 2012). On that account, an integrative analysis of front crawl sprint performance considering sex and two distinct skill levels in young swimmers has been conducted (**Chapter 6**). This was done aiming to observe the main effect of gender and skill level in choosing swimming solutions, evidenced by the development of some variables instead of others. In fact, it was proposed that intrinsic dynamics might reflect the organizational tendencies of an individual (Kelso, 1991). Consequently, following the rationale of the pilot study above (**Chapter 5**), a broader approach was conducted in this chapter, expecting to find the variables that could be more advantageous to achieve better performances, considering swimmers' gender and skill level.

The following studies resulted from an intervention conducted in three different swimming age-groups (plus the control group) with distinct tasks. Swimmers from various teams had to be requested to achieve an adequate sample size, although that choice was quite careful, based on groups with similar training session characteristics (frequency, volume, and intensity) and by the swimmers' level. In the following studies, different training sessions were accomplished, being approved by the respective coaches and always performed under supervision. These studies analysed the effect of different sessions on front crawl coordination for eight weeks, based on manipulating constraints, since in representative learning designs it could lead to a development of individualized movement responses directly related to the performer's intrinsic dynamics (Seifert, Button, & Davids, 2013). Also, in the literature, few intervention studies had been conducted in young swimmers, and to the best of our knowledge, none of them were done focusing on front crawl coordination.

Considering studies that indicated speed and SF as the main influencing parameters on front crawl swimming coordination (Potdevin et al., 2006; Seifert & Chollet, 2008), for eight weeks a young swimmers group performed specific sessions based on task manipulation (**Chapter 7**). Focusing on maximal speed, swimmers performed a set (2 x [6 x 25-m]) in front crawl technique (all movement), where SF was manipulated while maintaining the same speed. Concurrently, another age-group, the control group, was performing the normal training sessions, without that additional set. At the end of the 8-week training sessions (twice a week, a total of 16 training sessions), the results were analysed, aiming to understand the changes of that additional set. It was expected to observe different swimming coordination patterns and also a high coordinative variability of patterns in the group that performed the additional sessions.

In addition, and following the theories that highlighted that the central nervous system uses muscle synergies to simplify the movement coordination (Kugler et al., 1980), strength was also considered in the front crawl swimming coordination analysis. Accordingly, a study was carried out to develop two different strength training for eight weeks (twice a week, totalling 16 training sessions) in young swimmers (**Chapter 8**). This study developed a specific strength training program in water and a more traditional strength training on land conducted at the gym. With these two different variations of training, it was intended to observe which type of training induces more changes in front crawl swimming coordination, but also which is the type of training that increases more the young swimmers' strength, leading to increases in performance. It was expected that the more specific strength training sessions (in water strength training) were the ones that would induce more changes in the front crawl coordination patterns and swimming performance.

Chapter 2.

Front crawl swimming coordination: A Review.

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Submitted for publication on Motor Control.

Abstract

Coordination has a long history in motor control theories. Over the last 30 years, the dynamical systems theory and the ecological psychology have provided fruitful insights to understand how coordination patterns emerge, persist and change in relation to a set of constraints. In swimming, drag represents environmental constraints that strongly influence coordination. Based on theoretical frameworks and anchored in the sciences of complexity, it sought to understand how swimmers coordinate their limbs to propel themselves and to deal with active drag. The purpose of this systematic review was to perform the state of the art concerning coordination between upper limbs in front crawl, the most used swimming technique on training and competition conditions. This will be done focusing on methods used to analyze this specific swimming technique and on the interaction between coordination and biomechanical and physiological parameters, in particular those relating to gender, skill level and maturation stage.

Key words: swimming, coordination, measurement, biomechanics, physiology, expertise.

Introduction

Over the last century several approaches have been arising aiming to define coordination (psychomotor, neuromuscular and motor skill perspectives; Schmidt & Timothy, 2005), based on the assumption that it is more than a control of a sum of components. A functional viewpoint highlights the synergy between muscles, i.e., when muscles are united in a common goal (Haken, 1983), occurring when an error created by a system component (with a specific purpose) is compensated by another component changing to ensure task completion (Latash, Scholz, & Schöner, 2002). Therefore, synergy is related to the relatively independent degrees of freedom temporarily behaving as a single functional unit (the coordinative structure or coordination pattern; Turvey, 2007). Following Kelso (1995), those coordination patterns appear through a self-organization rather than prescribed by some sort of executive regulating agent. However, different components analysis enable identifying low-dimensional macroscopic variables (Haken, 1983), defining stable and reproducible relationships occurring among sensorimotor system components, as it searches for and adopts functionally preferred coordination or attractor states (e.g. Kelso, 2009).

In cyclic sports, inter-limb coordination is a central concern, aiming to achieve and maintain high race speeds, resulting in resistive and propulsive forces interaction (Toussaint & Beek, 1992). Regarding front crawl, the fastest and most studied swimming technique, in which 85% of the total propulsion is generated by upper-limbs (Bucher, 1975; Deschodt, Arsac, & Rouard, 1999; Toussaint, 1992), coordination is essential to organize the transition between under and above-water motions, managing the propelling time (Seifert, 2010). In addition, although coordination has not been found to be directly correlated to propulsion, its function to minimize hydrodynamic drag and to increase propulsion is fundamental (Lerda & Cardelli, 2003). It has already been shown that when increasing drag, swimmers should favor both an efficient hydrodynamic position and a propulsive continuity, thus avoiding high intra-cyclic velocity variations (IVV; e.g. Seifert, Schnitzler, Alberty, Chollet, & Toussaint, 2010; Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010). In turn, speed derives from the stroke length (SL) and stroke frequency (SF) product, allowing different combinations that could lead to distinct coordination pattern adaptations.

Knowing that different swimmers can display the same force and/or power output when exhibiting different upper-limb coordination patterns (Seifert, Toussaint, et al., 2010), it could be observed a probably different impulse force (the product between time and force magnitude) (Alberty, Sidney, Pelayo, & Toussaint, 2009). Considering that propulsive impulses per time unit cannot be increased indefinitely and the mechanisms of energy supply are used almost to their fullest limits, upper-limb coordination seems essential for IVV reduction (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005). Complementarily, as hydrodynamic drag is constantly fluctuating, a proper swimming technique should be sufficiently flexible and adaptable to enable emerging coordination patterns, modifying according to constraints acting on the swimmer (Glazier, Wheat, Pease, & Bartlett, 2006). Therefore, physiological factors have been also indicated as movement influencing components, with evident changes being observed in front crawl coordination on the transition through the anaerobic threshold (Figueiredo, Morais, Vilas-Boas, & Fernandes, 2013). This suggests that physiological capabilities, as the ability to withstand fatigue, might also be considered a constraint leading to coordination changes.

Furthermore, subject's characteristics (as age, gender, anthropometrics and experience level) should also be considered when analyzing swimming coordination, since the organismic constraints could influence performance. It is known that men have a higher strength level comparing to women, which helps them to produce higher power output and SL (Seifert, Barbosa, & Kjendlie, 2011; Simmons, Tanner, & Stager, 2000), and that maturation stage affects performance (Silva et al., 2012b).

Hence, skill acquisition seems to be linked to the redundant degrees of freedom mastering (Bernstein, Latash, & Turvey, 1996), due to the dynamic and constant search for functional coordination states (e.g. Kelso, 2009). Moreover, it was observed that different swimmers could achieve the same performance outcome with diverse motor organizations, suggesting that there is not an ideal coordination pattern to impose or teach (Seifert et al., 2014a). In turn, it has been argued that the swimming environmental constraints (e.g. drag) and the performing task (e.g. a specific race), together with the organismic constraints, will guide and shape the individual coordination pattern.

Studies on front crawl swimming have been analyzing the upper-limb coordination through different methods, with a major limitation of analyzing only temporal characteristics (e.g. Chollet, Chalies, & Chatard, 2000), neglecting the integrated temporal and spatial components analysis (Figueiredo, Seifert, Vilas-Boas, & Fernandes, 2012). The current study aimed to conduct a systematic review seeking to answer to the following questions: (i) how has swimming coordination been measured? (ii) how do biomechanical variables interact with swimming coordination? (iii) how are physiological variables linked with swimming coordination? and (iv) do gender, skill level and maturation stage limit the coordination mode adopted?

Methods

An electronic search was conducted during March 2017 including all the relevant studies from 1980 until that date. A combination of "swim*" and "coordina*" was used, with the asterisk meaning variability on the final part of the word. The most relevant literature in front crawl coordination was collected using SPORTDiscus™, CINAHL®, MEDLINE, Scopus™, Science Direct, Academic One File, ISI Web of Science and PubMed™, focusing in academic journals and conference proceedings (including Biomechanical and Medicine in Swimming and International Society of Biomechanics in Sports Symposiums). The inclusion criteria comprehended English written studies with swimmers of all performance levels, gender and ages. As coordination could be evaluated through different methods, and not all of them were used in swimming with the same regularity, its discussion was also included. Studies on dry land coordination, with animals, disable swimmers, reviews, overviews, master and PhD thesis were excluded.

Results

A total of 2916 journal papers and conference proceedings were identified in the electronic databases when using the above mentioned keywords (Figure 1). A search engine has been used and the duplicated data were immediately excluded, remaining 2813 files that were transferred to a reference managing software (Endnote X7, Thomson Reuters, USA). From those, 1363 studies were excluded after the title analysis, since they were not related to the specific topic of interest (animal testing, studies related to other sports and clinical topics). After abstract analysis, 84 studies were selected to full text reading, from which 10 were excluded: six were reviews or overviews, one has not specified the coordination method employed and two were duplicated (abstract and short paper published in the same congress), remaining 73 files (Table 1).

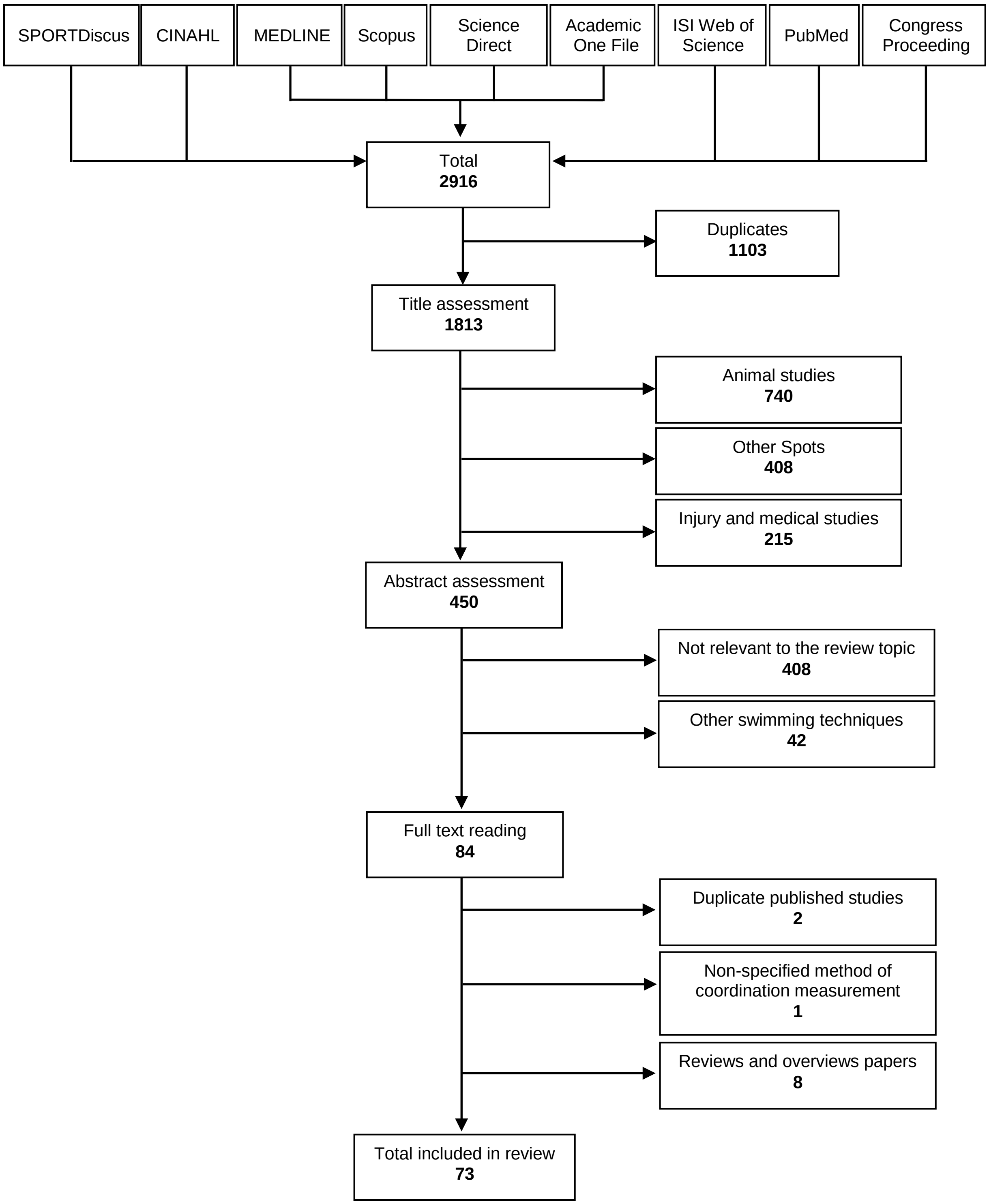

Figure 1: Flowchart of front crawl swimming coordination literature search

Table 1. All the studies found with the aim of analyzing front crawl swimming coordination.

Authors	Parameters analysed	Outcome	Sample	Focus	Major Findings
Chollet et al., 2000	Velocity, skill level and leg kick	IdC	40 elite swimmers: G1: 14 (10 boys and 4 girls); G2: 15 (10 boys and 5 girls); G3: 14 (9 boys and 5 girls)	Describe IdC and how it varies with velocity (800m, 100m and 50m), performance level and type of leg-arm synchronization.	IdC increased with velocity, performance level and SR. It also increased when SL decrease. The increase in IdC was associated with a change in arm-leg synchronization from a two-beat kick to a six-beat.
Millet et al., 2001	Skill level and velocity	IdC	19 elite triathletes and 15 elite swimmers	Compare the arm coordination in elite triathletes and elite swimmers between 80% and 100% of their individual maximal velocity.	Similar IdC changes as a function of velocity were observed in both groups, however, at maximal velocity triathletes reduced IdC while swimmers increased. At the highest velocities, triathletes increased their propulsive phases but less than swimmers. They also increased their recovery phase while swimmers reduced it.
Lerda et al., 2001	Breathing	IdC	24 male swimmers (12 experts and 12 non-experts)	Assess the effect of breathing on arm coordination and the relative duration of stroke phases with and without breathing.	Breathing leads to discontinuity in propulsion. Expert swimmers have a greater capacity to adapt breathing to the biomechanical constraints, attempting to limit disequilibrium and favor glide. At slower speeds, less expert increase recovery time and expert entry and catch.
Wannier et al., 2001	Arm and leg coordination	EMG	13 healthy subjects	Analyze the arm and leg coordination during different forms of locomotion in humans.	Arms and legs movements are always in anti-phase mode.
Sefert et al., 2003	Gender, velocity	IdC	51 elite swimmers (38 male and 13 female)	Analyse the differences between genders in arm-coordination and their adaptations when the imposed swimming velocity increased.	Males showed higher IdC values comparing with females. With the increasing velocity, males increased both propulsive phases and decrease both non-propulsive phases, whereas females only increase the push and decrease the entry and catch phase. Females could not achieved supperposition mode in opposition to males.
Chollet et al., 2003	Velocity, skill, drag, breathing	IdC	Study 1: 43 national swimmers; Study 2: 19 thriatletes and 15 swimmers; Study 3: 12 triathletes; Study 4: 24 male (12 expert and 12 non-expert)	To show the usefulness of the IdC to evaluate arm propulsion discussing four studies	Study 1: with increasing velocity, swimmers change from catch-up to supperposition. This changes are more pronounced in expert swimmers. Study 2: no significant diferences between triathletes and swimmers were found regarding coordination. Study 3: wet swim promote glidding phase. Study 4: IdC was higher when swimming in apnea than when the swimmer breath (+3.05%)

Potdevin et al., 2003	SR, velocity	IdC	Study 1: 30 swimmers (11 national and 19 non expert); Study 2: 9 swimmers (6 males and 3 females)	Assess the effect of SR on the reproducibility of swimming velocity and IdC	Study 1: SR seems to strongly determine velocity, particularly when SR is higher than 40 cycles·min^{-1}. Study 2: between 20 and 50 cycles·min^{-1} only catch-up coordination is adopted. Above that SR value, supperposition mode emerges.
Alberty et al., 2003	IVV and fatigue	IdC	17 elite swimmmers	Detect technical changes, through the IVV and the arm coordination, after an exhaustive exercise.	To compensate the decrease of velocity, swimmers who were not alowed to increase SR changed arm coordination. Muscular endurance is one of the main limiting factors which is responsible for maintaining technical skill during high intensity exercise.
Lerda & Cardelli, 2003	Breathing, skill level and velocity	IdC	36 male adult swimmers (18 more expert and 18 less expert)	Measure the durations of inhalation, exhalation and apnea during the different stroke phases, regarding skill level, velocity and inhalation side.	The relationships of stroking parameters to durations of breathing phases during performance of the front crawl change as a function of inhalation side, skill and swim velocity. The IdC increased with the velocity.
Hue, Benavente & Chollet, 2003	Wet suit	IdC	12 national and international male triathletes	Analyse the swimming technique of triathletes with and without wear suits.	SR and IdC did not change with the use of a wet suit.
Hue, Benavente & Chollet, 2003	Skill and velocity	IdC	12 male triathletes and 29 male swimmers	Compare IdC values between triathletes and swimmers at different velocities.	In every awim velocity IdC remain in catch-up for both groups, but swimmers showed opposition mode at maximal velocity. IdC increased with velocity, although in swimmers this increase was greater and triathletes lower IdC values at maximal velocity.
Seifert, Chollet & Bardy, 2004	Velocity	IdC	14 elite adult male swimmers	Analyse (1) whether IdC could be considered an order parameter; (2) the different attractive states or prefered arm coordination and transition between them; (3) whether velocity, SR, SL and SR/SL could be considered a control parameters.	An abrupt change in coordination pattern occurred at the critical velocity of 1.8 ms^{-1} (corresponding to the 100m pace): swimmers switched from catch-up to relative opposition. This was linked to an increase in SR and a decrease in SL, indicating that SR, SL, SR/SL and velocity could be considered as control parameters. These parameters can be manipulated to facilitate the emergence of a specific coordination.
Seifert, Boulesteix & Chollet, 2004	Gender and velocity	IdC	24 adult swimmers (14 men and 10 women)	Analyse (1) differences in IdC between elite men and women when imposing swim velocity; (2) if these differences were only due to technical modifications or also to anthropometric data.	At the same effective velocity, men have a greater catch-up coordination due to a different motor organization independent of biomechanical constraints. A greater height and arm span in men can explain the different adaptation of arm coordination. The women's catch-up coordination should not be identify as a "worse coordination".

Seifert, Chollet & Allard, 2005	Symmetry and breathing	IdC	28 adult male swimmers (10 elite, 10 mid-level, 8 elite non-expert)	Analyse the reationship among arm symmetry, arm dominance and preferential breathing side in a 100 m front crawl, as a function of expertise.	Most swimmers showed asymmetric arm coordination, being more related to breathing laterality and arm dominance, with different profiles noted. Breathing of non-expert amplified their asymmetric coordination. Conversely, elite swimmers, who had higher and more stable velocity and SL, a high IdC and lower breathing frequency, managed their race better than non-expert and their asymmetric arm coordination was not disturbed by breathing actions.
Seifert, Boulesteix et al., 2005	100m	IdC	12 elite male swimmers	In 100 m (1) establish the relationship among velocity, SR, SL and IdC; (2) the evolution in IdC and arm-leg coordination.	Within the four lengths of the 100 m trial, elite men tended to reduce the decrease in velocity and SR by stabilizing SL. With faigue, swimmers adopted their stroke phases organization to maintain superposition arm coordination.
Alberty et al., 2005	IVV and Fatigue	IdC	Test 1: 17 elite (13 males and 4 females) Test 2: 9 elite swimmers	Assess the modifications of IdC and IVV during an exhaustive exercise.	Although the IdC remained in catch-up mode throughout the different tests and despite the decrease of velocity, IdC increased significantly as fatigue developed.
Nikodelis et al., 2005	Skill level and speed	End-point trajectories	12 adult swimmers: 5 elite (2 males and 3 females) and 7 novice (6 males and 1 female)	Analyse the inter-arm coordination with a dfferent method and the relationship between coordination and skill level and swimming speed.	With the increasing velocity, anti-phase mode become stronger in both groups. The level of swimming skill was not affected by the strength of coupling between the hands, although elite swimmers showed more consistent and symmetrical hand tramjectories.
Potdevin et al., 2006	SR and skill level	IdC	27 elite swimmers (13 non-expert and 14 expert)	Analyse the IdC differences in expert and non-expert swimmers when imposing SR.	Superposition mode was more linked to higher SR values, rather than skill level. The adoption of a superposition mode also appeared to be linked to the ability to accelerate the hand and to maintain a long hand trajectory at a high SR values.
Tella et al., 2006	IVV with and without fatigue	IdC	17 juvenille swimmers (10 males and 7 females)	Examine changes in IVV in high intensity efforts with and without fatigue and its relation with IdC.	IdC increased with fatigue.
Schnitzler et sl., 2006	Swimming pace, IVV and skill	IdC	2 higly-trained female swimmers of different skill level	Determine whether skill level could be partly explained by an inadequate adaptation of motor coordination changing environmental constraints.	The increase in IdC with swimming velocity was greater for the expert. Less skilled swimmer showed higher IVV that increase with swim pace, whereas IVV did not vary with swim pace in expert swimmer.

Seifert, Chollet & Chatard, 2007	100 m, gender and skill	IdC	36 adult swimmers: G1: 12 high level males; G2: 8 medium level males; G3: 8 low level males; G4: 8 high level females	Compare (1) changes in velocity, SL, SR, IdC and leg kick in 100 m in different skill level swimmers; (2) differences between males and females.	During a 100 m front crawl: (1) high performance level was characterized by high and stable values of SL and IdC; (2) genders were differentiated by the greater SL of males compared with females.
Seifert, Chollet & Rouard, 2007	Swimming pace, gender, anthropometry and expertise	IdC	42 adult swimmers (15 elite men, 15 mid-level men, 12 elite women)	Investigate the effects of constraints on IdC regarding gender, anthropometric and expertise effect.	Organismic constraints were related more to gender and expertise than to anthropometry as no significant regression was found between IdC and height, nor between IdC and arm span; SR is the best predictor of IdC and pace was the second, being observed a transition in IdC from catch-up to superposition at 200 m; IdC increased when speed and SR increased, however, even at high speeds, mid-level men and elite women always exhibited catch-up mode.
Strzala et al., 2007	Young swimmers and pace	IdC	30 young swimmers (G1: 15 boys and G2: 15 girls)	Analise the 400 m, 100 m and 25 m in elite young swimmers.	Front crawl swimming velocity at different distances depends equally on SL or arm movement trajectory, as well as the individual SR and IdC.
Schnitzler, Seifert et al, 2008	IVV, velocity and gender	IdC	12 elite swimmers (6 males 6 females)	Determine (1) the relationship between IdC, IVV and swim pace; (2) the differences between genders.	IVV was maintained whatever the velocity and in response to the variations in both propulsive and drag. This stability may be the consequence of adaptations in arm propulsive time and IdC. Although the mean values of IdC and IVV with different swim paces might be sensitive to anthropometric and gender characteristics, the stability of IVV with swim paces and velocity may be an interesting indicator of swimming technique efficiency and a means to determine whether or not adaptations in coordination have been adequate.
Chollet et al., 2008	Breathing, symmetry, injury	IdC	13 expert male swimmers	Identify the relationship between breathing laterality and coordination as a function of the symmetry of medial rotator muscle force in the shoulders.	Force symmetry and stroke phase duration are related to breathing laterality more in sprint than in middle-distance swimmers. The risk of injury in shoulder seemed higher in sprint specialists.
Morais et al., 2008	Fatigue and IVV	IdC	3 elite swimmers	Asses (1) modifications in IdC during the Time Limit test (to exhaustion) at the minumum velocity of VO_2max; (2) the relationship between IVV and IdC during the test.	IdC seems to reflect the effects of exercise to exhaustion on swimming technique, being a useful tool for coaches and scientists in order to better understand the technique modifications under fatigue conditions. Muscular endurance limitations led swimmers to try to find the most efficient arm coordination for a particular context.

Seifert et al., 2008	Breating and symmetry	IdC	11 male sprint swimmers	Determine the effects of unilateral, axed and bilateral breathing patterns on IdC, focusing on arm coordination symmetry.	A unilateral breathing to the preferential side led to asymmetric coordination and this was even greater when swimmer breathed on his non preferential side. Conversely, the axed and bilateral breathing patterns led to coordination symmetry.
Alberty et al., 2008	Fatigue, SR, SL	IdC	10 adult swimmers (8 males and 2 females)	Analyse IdC during exercises at constant speed with or without a controlled SR.	IdC did not change during the time-to-exhaustion tests performed when controlling SR during a constant speed exercise.
Tourny-Chollet et al., 2009	Symmetry index and force	IdC	13 male adult swimmers	Analyse the relationship between breathing laterality and motor coordination symmetry as a function of the symmetry of medial rotator muscle force in the shoulders.	Two profiles emerged providing skill level indication: swimmers for whom (i) breathing laterality seemed to be related to force symmetry and stroke phase duration; (ii) the impact of breathing laterality was not in accordance with the force symmetry or stroke duration because these last remained symmetric.
Alberty et al., 2009	SL, SR and fatigue.	IdC	10 adult swimmers (2 females and 8 males)	Analise the changes in SR and SL values during a three times to exhaustion at predetermined speeds (95 %, 100 % and 110 % of the maximal 400 m)	In constant speed, fatigue led the SR and IdC to gradually raised, increasing the duration over which the propulsive force acted per distance unit as the force capacity was reduced. With the inreasing fatigue, SR and IdC are strategies to solve the problem of generating an adequate propulsive impulse.
Fernandes et al., 2009	Breathing and young swimmers	IdC	15 young swimmers	Assess IdC in young swimmers observing the differences between breathing and non-breathing cycles.	Breathing action increased propulsive discontinuity.
Gourgoulis et al., 2009	Paddles in females	IdC	10 female adult swimmers	Investigate possible alterations in IdC in female front crawl swimmers when diferent sized hand paddles were worn.	Despite the increasing velocity, IdC remained in catch-up. The larger hand paddles led to a decrease in the duration of the entry and catch phase. Hand-paddles should not be used as a tool to alter the time of the propulsive forces generated from the two arms.
Lemaitre et al., 2009	Apnea	IdC	4 adult male swimmers	Determine the benefits of 3 month apnea training in swimmers whith no experience in apnea.	The training led to improve swimming technique, with a greater propulsive continuity between the two arms.
Schnitzler, Seifert & Chollet, 2009	400 m and gender	IdC	12 elite swimmers (6 males 6 females)	Examine the variability of physiological, perceptual, stroke cycle and coordination parameters.	Expert swimmers were able to reproduce not only stroke cycle but also coordination parameters at the 400 m pace. Coordination parameters remained stable despite the emergence of fatigue.
Seifert & Chollet, 2009	Swimming pace, SR and SL	IdC	48 elite male swimmers (4 groups of 12 specialists)	Model the relationship among SR, SL, IdC and speed in the four strokes.	The relationship among SR, SL and speed correspond to a quadratic regression. SR, SL and speed may influence swimming coordination.

Schnitzler et al., 2010	IVV and skill level	IdC	22 male swimmers (10 eltite and 12 recreational)	Analyse whether IVV, IdC and the changes in these parameters across swim pace would discriminate performance level.	Expert swimmers were able to maintain stable IVV while increasing IdC, whereas in recreational swimmers IVV increased significantly but their IdC did not significantly change.
Komar et al., 2010	Fatigue, speed, SR and SL.	IdC	6 national adult swimmers	Relationship between IdC and energy cost.	The increase of energy cost led swimmers to change their motor organization, increasing IdC and SR and decreasing SL
Seifert, Komar et al., 2010	Swimmer specialty and energy cost	IdC	12 elite swimmers (6 long-distance 6 sprinters)	Analyse the effect of swimmer specialty on energy cost, arm coordination and stroking parameters.	Swimmers increased SR and decreased both SL and IdC with increasing velocity. Sprinters are accustomed to a greater speed range, and reach higher maximal speeds. They thus displayed lower performance, lower SI, higher IdC and a greater increase in IdC than the long-distance.
Seifert & Chollet, 2010	Swimming pace, SR and SL.	IdC	20 adult male (7 regional, 10 national, 3 international; 12 sprinters and 8 distance swimmers)	Model the relationships between IdC and speed for swimmers of various skill levels and specialty.	The IdC value by itself does not indicate the swimmer's motor skill, but should be used as an indicator of performance or efficiency, such as SR, SL, SI, IVV and the propulsive efficiency.
Seifert, Toussaint et al., 2010	Power, swim efficiency, skill level and velocity	IdC	14 adult male swimmers (7 national and 7 regional swimmers)	Analyse (1) how national and regional swimmers organized their stroke to increase velocity. (2) whether, for a given speed, the stroke organization of the national swimmers would be more efficient.	For both groups, when increasing speed their propulsive continuity and hand speed also increased, applying a greater mechanical power output to overcome active drag. National swimmers appeared more efficient and they also showed greater IdC. The higher hand speed of the regional swimmers may have reflected hand slippage through the water, suggesting that great hand force and speed need to be associated with a correct path and orientation of the hand.
Seifert, Schnitzler et al., 2010	Drag, propelling efficiency	IdC	13 adult male swimmers	Analyse (1) IdC changes as a function of active drag; (2) wether these changes are relate to propelling efficiency.	IdC was not linked to propelling efficiency when swimming with arms-only, but related to active drag. Thus, a high IdC does not guarantee higher speed as the efficiency of the propulsion can be very low.
Figueiredo et al., 2010	Pace	IdC	6 male elite swimmers	Assess (1) the IdC during a 200 m maximal effort; (2) its interplay with the stroking parameters.	IdC remain in catch-up during the whole effort. Fourth lap exhibited an increased IdC possible due to fatigue. However, it further reflected more time spent during the propulsive phase than greater force generation as the velocity and SL decreased in the last 50 m of the 200 m.
Fernandes et al., 2010	Energy cost	IdC	7 high-level swimmers	Assess the relationship between the IdC and the energy cost duing an incremental protocol.	IdC and energy cost increased with the increased velocity, presenting a very high relationship between them. However, when removing the effect of velocity, that relationship was not significant.

Schnitzler, Seifert & Chollet, 2011	Velocity, SL and skill level	IdC	16 male swimmers (8 expert and 8 non-expert)	Determine (1) the contribution of IdC in 400m; (2) the influence of IdC on performance and SL values.	IdC and stroke phase durations differentiate performance level during a maximal 400m front crawl swim.
Telles et al., 2011	Drag	IdC	11 adult male swimmers	Investigate the effects of hand paddles, parachute and hand paddles plus parachute on the relative duration of right and left arm-stroke phases and the IdC at maximal effort.	Hand paddles, parachute and hand paddles plus parachute used when swimming at maximal intensity do not significantly influence the organization of the stroke phases in both arms. However, IdC was altered from catch-up to opposition when parachutes and hand paddles plus parachutes were used, highlighting a greater propulsive continuity as a chronic effect.
Schnitzler, Brazier et al., 2011	Strength	IdC	7 elite adult male swimmers	Investigate the effect of pace and amounts of resistance (as provided by a parachute) on SR, SL, IdC, stroke phases and force impulse, peak propulsive force parameters.	The additional resistance provided by a parachute provokes a reorganization in swimming pattern that would not be typical in normal swimming training, enhancing both coordination and force development. But these changes occurred only near maximal speed, suggesting that the application of this type of training device should be limited to high-intensity swimming.
Dominguez-Castells et al., 2012	Strength, biomechanics	IdC	18 male college swimmers	Analyse (1) to what extent the use of different loads modifies freestyle stroke and coordination during semi-tethered swimming; (2) whether those changes are positive or negative to performance.	IdC rose significantly with load, presenting a quadratic trend. Stroke and coordination parameters were not modified to a great extent under certain load. Resisted training would be beneficial to coordination.
Figueiredo et al., 2012	Swimming pace, fatigue SR and SL.	CRP	10 adult male swimmers	Examine the inter-subject variability in inter-arm coordination at high intensity.	To achieve the same velocity, it was observed different combinations of SL and SR, promoting the occurrence of asymmetries, which were also caused by the inherent breathing pattern.
Silva et al., 2012	Young swimmers	IdC	114 young swimmers (56 boys: 36 pubertal and 20 post-pubertal; 58 girls: 24 pubertal and 34 post-pubertal)	Characterize technique in 11–13 years old swimmers by assessing velocity, SR, SL, SI and IdC at very high intensity.	Young swimmers used the catch-up arm coordination mode when performing front crawl at the 50m pace, showing an evident lag time between propulsive arm phases.
Figueiredo Morais et al., 2013	Energy cost	IdC	12 elite swimmers (6 males and 6 females)	Explore how physiological, biomechanical and IdC measures change from below to above lactate threshold and the way in which they inter-relate.	The inflection points in the IdC, SL, SR, and VO_2 net were coincident with the lactate turn point, showing the interplay of the parameters resulting from the increase in velocity.

Figueiredo Pendergast et al., 2013	biomechanics energetic, coordinative and muscular factors	IdC	10 elite swimmers	Determine the relative contribution of biomechanical, energetic, coordinative, and muscular for the 200m front crawl performance and each of its four laps.	As velocity and the SL-SR ratio changed, IdC increased in the final of the 200m event. This changes were related to the development of fatigue, showing that an effective front crawl swimming technique must be sufficiently flexible and adaptable.
Formosa et al., 2013	Symmertry, gender and breating	Net drag force and Symmetry Index	20 elite adult swimmers (10 males and 10 females)	Analyse the influence of gender and breathing on stroke coordination and symmetry by using a traditional timing method and an instantaneous net drag force profile.	Significant differences existed when comparing timing symmetry index to the instantaneous net drag force symmetry index within the breathing condition only, being suggested that both measures should be used. Gender did not influence coordination, the symmetry index for timing, or instantaneous net drag force within the breathing and non-breathing condition.
Figueiredo, Toussaint, et al., 2013	IVV, efficiency and energy cost	IdC	10 elite male swimmers	Establish the relationship between some well-accepted efficiency parameters (IVV and Froude efficiency), energy cost and IdC in a 200 m race.	With the increasing fatigue, during the 200 m, swimmers showed a stable IVV, a decrease in velocity, SL, SR, propelling efficiency and an increase of IdC. Direct relationships between energy cost and IdC for the second and fourth lap were found. IdC and propeling efficiency showed to be significant for the within-subjects correlation and IdC and energy cost for the between-subjects correlation.
Bideault et al., 2013	Speed, gender and skill level	IdC	63 front rawl swimmers (48 males and 15 females)	Analyse variability considering speed and swimmer's characteristics (gender, skill level and swim speciallity).	Four clusters were differentiated regarding the organismics constraints (gender, skill level and swim specialty). Regarding enviromnental constraints, speed led to change coordination, which could be related to the increased drag. Race pace, which is a task contraint, also influence coordintaion adoption.
Gourgoulis et al., 2013	Drag	IdC	9 female swimmers	Assess the effect of sprint resisted on coordination and the fluctution of the instantaneous swimming velocity.	Sprint resisted does not lead to technical improvements as although resisted swimming cause an increase in IdC, the velocity fluctuations of the hip whithin a stroke cycle are not decreased.
Ribeiro et al., 2013	Velocity, SR, SL, IVV, drag	IdC	10 male swimmers	Examine the relationship between velocity, SR, SL, IVV, IdC, propelling efficiency and force production.	Force production requires increases in SR and in velocity. Coordination adaptations permitted high force outputs due to continuity of propulsive phases and IVV decreases were essential to produce higher values of force.
Figueiredo et al., 2014	Energy cost	IdC	30 long distance swimmers	Analyse the behavior of relevant kinematical parameters when swimming at Maximal Lactate Steady State (MLSS) intensity.	At MLSS intensity, IVV, propelling efficiency, SR and SLchanged, but IdC, values of trunk incline and the time allotted for propulsion per pool length remained stable along this typically aerobic effort.

Formosa et al., 2014	Symmetry and breathing	Net drag force and Symmetry Index	20 national elite swimmers (10 males and 10 females)	Compare results with IdC and net drag force regarding arm symmetry and breathing effect.	The majority of swimmers showed an asymmetrical net drag force stroke profile during breathing and non-breathing, favouring the breathing stroke side. Thus, breathing action increases propulsive discontinuity, although the asymmetry was less prevalent when examining only the timming symmetry index.
Matsuda et al., 2014	IVV and velocity	IdC	7 elite and 9 beginner adult swimmers	Examine whether the IVV was lower in elite swimmers than in begnners at different velocities and whether differences may be related to arm coordination.	IdC in elite swimmers increased more significantly than in begginners, being dependent of skill level. IVV was lower for elite swimmers and its values were not related to IdC.
Schnitzler et al., 2014	Fatigue, SL and SR	IdC	9 male swimmers	Analyze the effערct of 3months of aerobic training on spatio-temporal and coordination parameters.	Swim speed increased with a decrease in IdC, i.e. speed increase due to higher propulsive forces performed in each stroke rather than raising the time spent in each propulsive phase.
Seifert, Komar, Crettenand et al., 2014	Energy cost and flexibility	IdC	17 national swimmers (9 front crawl and 8 breaststroke specialis)	Analyze how expert swimmers are able to adopt an economic inter-limb coordination pattern and coordination flexibility.	Energy cost was lower for the preferred coordination; no ideal coordination patern was determined; when constraining coordination, it was observed compensatory strategy by legs kicks.
Silva et al., 2014	Velocity, SR, SL, young swimmers	IdC	18 young female swimmers	Determine which parameters are predominant to achieve better performances in young swimmers.	IdC were in catch-up for the entire sample. In young female swimmers, higher performances are linked to a greater SL, SI, mean and maximal force, shoulder flexion, better hydrodynamic profile and lower IdC.
Seifert et al., 2015	Drag, SR and velocity	IdC	20 national male front crawl swimmers	Examine the drag-IdC relationship using different mathematical models.	A significant positive linear regression between IdC and active drag was observed. However, a high IdC was not automatically synonymous of swimming with a high propelling efficiency and high speed, as a non-significant correlation between IdC and propelling efficiency was observed at maximal speed.
Barbosa et al., 2015	SR, SL, velocity	IdC	22 sub-elite swimmers	Analyse changes in swimming kinematics and interlimb coordination behavior in 3 different incremental tests.	Only catch-up coordintaion mode was observed on the entired tests, although IdC increased with increasing velocity. No diferences in kinematical and IdC values between the 3 step lengths were observed.
Ferchichi et al., 2015	Velocity, SR and SL	IdC	14 regional swimmers	Examine the effects of time of day on stroke parameters and motor organization in front-crawl.	It was shown that morning–evening variations of performance, with higher evening values for temperature, V, SR, and Idc possibly explaining the better performance at this time.

Dadashi et al., 2015	Skill, velocity, SR, SL and IVV	IdC and IMUs	9 well-trained swimmers	Characterise front-crawl swimming skill based on variability pattern of technique descriptors at different velocities.	It was indicated that IdC can be used as a predictor of performance only when swimmers of homogeneous expertise level are studied and suggest the scrutiny of both intra-cyclic velocity variation and cycle velocity variation as a requisite to study the motor adaptations of the swimmer in facing new constraints.
Figueiredo et al., 2015	Velocity, SR, SL, energy cost and young swimmers	IdC	103 young swimmers	Evaluate the determinants of front crawl swimming sprint performance by assessing young swimmers profiles using a cluster analysis.	Anthropometric variables were the most determinant for cluster solution, presenting a strong influence on sprint performance in these age group swimmers. Differences between clusters were also found in SL, SR, SI, CV and IVV. Coordination and propelling efficiency were similar between all clusters, not defining specific swimming sprint profiles.
Morouço et al., 2015	Symmetry and breathing	Net drag force and Symmetr y Index	18 young swimmers	Examine the magnitude of upper limb kinetic asymmetries in front crawl tethered swimming at maximal intensity.	The majority of the swimmers (66.7%) presented an asymmetrical force exertion, i.e., SI higher than 10%. A deeper analysis revealed that force asymmetry is most due to different force exertion in the first cycles of a maximal bout.
Franken et al., 2016	Swimming pace, SR and SL.	IdC	15 regional and national level swimmers	Compare IdC, propulsive time, stroke phases duration, SR, SL and average swimming speed over 200 m	The IdC value, as well as the entry and catch, push and recovery phases, did not change between laps. The pull phase increased over the race, but its increases were due to fatigue, since the T_{prop} values showed increases only when decreased swimming speed was identified.
Ribeiro et al., 2016	SR, SL, speed, efficiency, drag, fatigue	IdC	10 male swimmers	Conduct a biophysical analysis of front crawl performance at moderate and severe intensities.	Biomechanical parameters, coordination and metabolic power seemed not to be performance discriminative at either intensity. However, the increase in power to overcome drag, for the less metabolic input, should be the focus of any intervention that aims to improve performance at severe swimming intensity.
Seifert et al., 2016	Swimming pace, skill level.	IdC	5 swimmers and 5 triathletes	Examine behavioural between and within variability, to explore how swimmers with various specialty adapt to repetitive events of sub-maximal intensity.	Ten clusers were observed, with only two behavioural patterns shared between swimmers and triathletes. Swimmers tended to use higher hand velocity, IdC and pattern stability. Triathletes revealed bi-stability, switching to another pattern at mid-distance.
Silva et al., 2016	SF and speed	CRP and IdC	18 young swimmers	Analyse if speed and SF could control the inter-arm coordination pattern in front crawl swimming.	Speed exerted a greater influence in behaviour comparing to SF, at least within the ranges used.

Ribeiro et al., 2016	Skill, SF, SL, efficiency, energy cost and skill level.	IdC	16 male swimmers (8 national and 8 regional level)	Examine the behaviour of selected biomechanical, energetic and coordinative factors of high-and low-speed swimmers throughout an extreme intensity swim.	Speed, P_O, SF, SL, η_p and C profiles in 100-m maximal effort seemed not to discriminate the distinct high- and low-speed performances. However, high-speed swimmers are able to achieve greater P_O and a tendency for superior ηp (with consequent higher SF), leading to a distinct coordination profile along the effort.

From the 73 files included in this systematic review, 16 (21.9%) were conference papers and the remaining 57 (78.1%) journal articles. The sample configuration was in 82.2% of the studies, composed by elite or well-trained swimmers, where 35.0% (21 studies) included one or two other different skill level or specialty (four studies included triathletes). Studies analyzing only non-experts (two studies), mid-level (two studies) and young swimmers (eight studies), as well as triathletes (one study) were also included. The majority of the included studies (46.6%) analyzed 11 to 20 participants, while 27.4% evaluated more than 20 swimmers, with 50.7% including only male participants. It has been also found one case study and one interventional study.

Kinematic descriptors was the most used method to measure front crawl swimming coordination (totalling 93.2% studies with kinematics only), with the Index of Coordination (IdC) totalling 65 studies. Only one study (1.4%) used endpoint kinematics, another used Continuous Relative Phase (CRP) and two studies combined two coordination methods (one used combined two kinematic methods: IdC and CRP; and another combined kinematic and kinetic methods: IdC and endpoint kinematics; Table 1). Moreover, three studies (4.1%) used kinetic methods (evaluating the net drag force in free conditions and force production in tethered swimming). Only one study (1.4%) employed electromyography (EMG) using surface electrodes to measure muscle electrical activity.

A great amount of studies (77.0%) aimed to associate front crawl swimming coordination with some biomechanical or physiological variables, being the former: (i) speed, SF, SL, IVV and drag (including the effect of breathing action) the most used on correlational analysis (65 studies, 57.5%), showing part of or even all of that variables; and (ii) the latter related to fatigue and energy cost measurements have been analyzed in 22 studies (19.5%), while 26 studies (23.0%) were related to gender and skill differences (including young swimmers).

Discussion

The current study aimed to systematically review the methods used to assess front crawl swimming coordination, as well as to describe its relationship with biomechanical and physiological variables, gender, skill level and maturation stage. 78.1% of the selected studies were journal articles (composed by 11 to 20 participants), 82.2% comprised elite well-trained swimmers (from which 50.7% included only men and 12 studies did not define swimmers gender). However, it is well known that differences in anthropometric and muscle characteristics/capabilities between adult vs age-group and male vs female swimmers lead to different performance profiles. Thus, future studies should also include female and young swimmers, since only 5.5 and 11.0% studies (respectively) focused on these populations. In addition, research on the swimming learning process, particularly interventional studies, is also welcome to better understand the mechanisms of coordination pattern changes.

1. How has swimming coordination been measured?

Discussing the different methods to assess swimming coordination requires, firstly, the understanding of its concept. It could be described macroscopically, expressing the patterning of body and limb motions regarding the environmental objects and events, or microscopically, as the characterization of the configurations of tensile states or the patterning of cellular and vascular activities (Turvey, 1990). More specifically, coordination pattern can be seen as a function that organizes the initially independent system elements into a functional unit in time and space (Newell, 1996). The interest in this topic in swimming has only begun in the 21st century, although some studies had already focused on it before, particularly by highlighting some characteristics that have been exerting influence upon swimming coordination (Catteu & Garoff, 1977; Maglischo, 1993). The IdC method, firstly described by Chollet et al. (2000), provides information on the time gaps between the upper-limb propulsive phases, which in front crawl correspond to the mean value between the beginning of propulsion of one upper-limb cycle and the end of propulsion of the other, distinguishing the catch-up, opposition and superposition coordination modes (IdC < 0%, IdC = 0% and IdC > 0%, respectively).

Until now, IdC has been the most used method in swimming coordination research, totalling 90.4% of the studies included in the current review. Despite being easy to apply, this discrete tool is only sensitive to temporal changes (Seifert, 2010), expressing the upper-limb duration cycle in percentage values. Therefore, only the time gap between propulsive phases is measured, giving no information about the real time that swimmers spend propelling themselves and, more relevant, the quality of that time (e.g. the implemented force, hand path and speed). Hence, IdC does not provide information about coordination dynamics (attractors, stability and critical fluctuations; Guignard, Rouard, Chollet, & Seifert, 2017) and it is expensive, labor-intensive and time-consuming (involving frame-by-frame analysis of slow-motion video) to obtain each upper-limb phase time to quantify.

Recently, time analysis was complemented with spatial information using an inertial measurement unit (IMUs; Dadashi, Millet, & Aminian, 2015), a device that allows recording long time periods (up to 200 h at 100 Hz frequency and more than 8 h between two consecutive battery changes; James et al., 2011), permitting analyzing coordination dynamics. In fact, this could be an alternative method to IdC, as it is portable, less expensive and does not require digitalization procedures (with rapidly available results), allowing collecting data simultaneously from several swimmers, since no signal interference is observed (Dadashi et al., 2015; Favre, Jolles, Siegrist, & Aminian, 2006). Conversely, complex procedures could also be implemented, since the angular time series analysis (to have spatial-temporal information) should contemplate the drift, offset, sensor synchronization and a three-dimensional position determination (Guignard et al., 2017).

Another different swimming coordination analysis uses a three dimensional upper-limb computation of end-points trajectories and it is based on the assumption that linear relationships exist within segments or joints (Nikodelis, Kollias, & Hatzitaki, 2005). This method calculates the correlation coefficients between end-points trajectories by introducing time lags between data sets, providing indications of the relationship type between two joints or segments and their degree of coupling. However, it is not assumed that these variables change in synchrony during movement (Mullineaux, Bartlett, & Bennett, 2001). This method is proper to study complex movements, analyzing parts or the whole body, allowing evaluating almost any kinematic (position, speed and acceleration) and EMG data. Moreover, as this method does not require a time origin, no normalization procedure is necessary and it could be very useful for evaluating movements that have identical statistical properties, as well as for detecting motor invariants when few trials or participants are analyzed (Nikodelis et al., 2005). Conversely, some disadvantages arise, since transformation procedures are needed to its linearization and, if after the transformation the cross-correlation coefficient remains small (i.e. no linear relationship between the segments appears), cross-correlations are unsuitable (Snedecor & Cochran, 1989).

The angular displacement and angular velocity diagrams to assess each joint phase angle through continuous relative phase (CRP) were also used to analyze coordination (Figueiredo et al., 2012; Silva, Figueiredo, Seifert, & Fernandes, 2016). This method provides instantaneous changes during a swimming cycle (Glazier et al., 2006; Kelso, 1995) by subtracting the distal from the proximal segment phase angles (Glazier, 2006). As the angular velocity determination included phase angles assessment, CRP has temporal and spatial information (Hamill, Haddad, & McDermott, 2000; Hamill et al., 1999), enabling a higher dimensional and more detailed behavior analysis (Hamill et al., 1999) and a more sensitive variability dimension (Wheat, Bartlett, Milner, & Mullineaux, 2002). As a matter of fact, as the various swimming actions are synchronized via timing signals, coordinative structures are supposed to provide the appropriate timing and spatial coordination (Massion, Amblard, Assaiante, Mouchnino, & Vernazza, 1998). This is hard to relate conceptually (Mullineaux & Wheat, 2002; Tepavac & Field-Fote, 2001), as the type and the interpretation of the relationship among joints and body segments is not easy to accomplish. CRP computation requires cyclic and sinusoidal signals and, as a kinematic method, it does not provide information about forces.

There are two methods for force analysis: net drag force (Formosa, Sayers, & Burkett, 2014; Formosa, Sayers, & Burkett, 2013) and tethered swimming (Morouço, Marinho, Fernandes, & Marques, 2015), which enable measuring the resultant drag and propulsive forces (Fulton, Pyne, & Burkett, 2011), including the contribution of different time derivatives of motion (as stiffness, viscosity and inertia; Mussa-Ivaldir, 2000). Similarly, tethered swimming has been used to measure swimming propulsion and it has been considered a reliable method (Amaro, Marinho, Batalha, Marques, & Morouço, 2014; Kjendlie & Thorsvald, 2006), due to the testing similarities to ecological conditions, implying a similar use of all body structure and muscle activity pattern (Bollens, Annemans, Vaes, & Clarys, 1988; Dopsaj, Matkovic, Thanopoulos, & Okicic, 2003), showing a good test–retest reliability (Dopsaj et al., 2003). In addition to a simplified data treatment compared to kinematic data, these methods also provide information on upper-limb force symmetry. However, in net drag force, differences in studies have been found between kinetic and temporal results (through a symmetry index that identifies the coordination differences between breathing and non-breathing cycles), since most of the swimmers exhibited asymmetrical profiles with the first method and symmetrical with the latest.

Finally, the EMG methodology has the advantage of providing continuous information about muscle activity, enabling coordination dynamics analysis. As it indicates, electrical potential produced during muscle contractions, muscular contraction intensity, myoelectric manifestation of muscular fatigue and motor unit recruitment are possible to observe (Garcia & Vieira, 2011). However, electrodes isolation and the inherent cables or wireless signal (Figueiredo, Rouard, Vilas-Boas, & Fernandes, 2013) are considered a huge constraint, making this method difficult to use in water. Nevertheless, in general, system objectivity, validity and equipment reliability (or stability) should be considered to measure or develop measures in motor control (Schmidt & Timothy, 2005). However, in future studies, the method employed ought to be based on the question that is asked concerning movement coordination, knowing that all these methods complement each other.

2. How do biomechanical variables interact with swimming coordination?

Swimming performance can be described as the ability to swim a race, according to the rules, in the shortest time possible. Knowing that swimming speed is the product between SF and SL, swimmers seek to find the optimal combination to attain and maintain the maximal speed (Craig, Skehan, Pawelczyk, & Boomer, 1985), with minimal IVV (Figueiredo, Toussaint, Vilas-Boas, & Fernandes, 2013). This latter results from the balance of the propulsive and resistive forces that characterizes swimming (Vilas-Boas, Fernandes, & Barbosa, 2010). Therefore, swimmers have to minimize the hydrodynamic drag to better propel the body forward. In this sense, all these biomechanical variables exert some influence on propulsive upper-limb continuity, particularly on upper-limb coordination.

2.1. Speed, SF, SL and IVV

Speed was the most analyzed variable in coordination studies, totalling (directly or indirectly) 47 studies (64.4%), reporting a positive correlation among those variables (range between $r = 0.69$ and 0.99). Thus, when speed increased, upper-limb synchronization also raised, with IdC values closer or above zero (Schnitzler, Brazier, Button, Seifert, & Chollet, 2011; Seifert & Chollet, 2010) and a stronger upper-limb coupling in anti-phase mode (Figueiredo et al., 2012; Nikodelis et al., 2005). Those values denoted a shorter gap between propulsive phases (great propulsive continuity) as the result from entry and catch phase decreasing and elite swimmers have also shown , a recovery phase reduction (some non-expert and triathletes increased it; Millet, Chollet, Chalies, & Chatard, 2002). Nevertheless, not every swimmer has the ability to switch from catch-up to opposition, or even superposition mode. This transition was noticed to occur at ~$1.8 m \cdot s^{-1}$ with the whole body swimming (Seifert, Chollet, & Bardy, 2004) and at ~$1.5 m \cdot s^{-1}$ with upper-limbs only (Seifert & Chollet, 2010). In elite swimmers, this critical speed occurs at 100 m pace (Millet et al., 2002; Seifert, Boulesteix, & Chollet, 2004; Seifert, Chollet, & Rouard, 2007), highlighting the differences in coordination patterns between long, mid-distance and sprint paces (Seifert, Chollet, et al., 2004).

Inversely related to speed, the body rolling action (Psycharakis & Sanders, 2008), which is important for a swimmer to breathe properly (Yanai, 2001), influences the hand speed negatively in the pull phase by -48% (Payton, Baltzopoulos, & Bartlett, 2002). This phenomenon limits the hand interaction with the water that has not already acquired kinetic energy (Hay, Liu, & Andrews, 1993), which could lead to modifications in the movement pattern. Therefore, a faster hand displacement occurs with the increasing speed, which in some cases could be linked to a hand slippage through the water, suggesting that a greater hand force and speed need to be associated to a correct path and hands orientation (Seifert, Toussaint, et al., 2010). When a superposition coordination occurs due to a hand slippage during the pull phase, this is not an efficient mode (Seifert, Chollet, & Rouard, 2007). Thus, it would be interesting to complement such temporal indicators with force information.

Only one study analyzed coordination between upper- and lower-limbs using EMG when swimming (i) freely; (ii) with two fins; (iii) only one fin; and (iv) simulating swimming when suspending (Wannier, Bastiaanse, Colombo, & Dietz, 2001). In all conditions, an anti-phase mode in ipsilateral limbs was observed, but speed and SF were not indicated, suggesting that athletes used their preferred. Complementarily, although not aiming characterizing coordination, a study noted that upper- and lower-limbs were coupled when changing constraints (e.g., wetsuit and fatigue), suggesting a strong coordination pattern between them (Chollet et al., 2000; Hue, Benavente, & Chollet, 2003b; Millet et al., 2002). A constant frequency ratio between lower- and upper-limbs was observed, with 1/1, 2/1, 3/1, 4/1 or even 5/1 combinations, with two-, four- and the six-beat kick being the most used patterns by swimmers and triathletes. However, the latter were not able to change their kicking pattern with the increasing speed, not even when wearing a wet suit (Hue, Benavente, & Chollet, 2003a), in opposition to swimmers, who used only the six-beat kick at the highest speeds (Millet et al., 2002), independently of upper-limb modifications (Chollet et al., 2000).

SF and SL and their combinations depend on a range of factors such as anthropometric characteristics, muscle strength, physical conditioning and swimming economy (Pelayo, Alberty, Sidney, Potdevin, & Dekerle, 2007). Simple to measure, they are indicators of the underlying motor processes and their combination reflects swimming technique. Consequently, their ratios can be associated with various coordination types (Alberty et al., 2008), as their changes are closely related to the time spent in the different cycle phases. A strong positive correlation ($r = 0.86$) was found between SF and speed (Keskinen & Komi, 1993), and similarly, higher and positive correlations have been found between IdC and SF (e.g. $r = 0.54$, Chollet et al., 2000; $r = 0.75$, Millet et al., 2002; $r = 0.76$, Seifert, Chollet, et al., 2004). This direct relationship between SF and speed with IdC suggests that they could be considered as control parameters in front crawl coordination, i.e., they could control the system in a non-specific mode, being capable to change system behavior (Kelso, 2009). Conversely, negative correlations with SL have been reported (e.g. $r = -0.52$, Chollet et al., 2000; $r = -0.58$, Millet et al., 2002; $r = -0.71$, Seifert, Chollet, et al., 2004), which was an expected result since SF and SL are covariants, i.e. for same speed when SF increases, SL decreases and vice-versa.

Indeed, speed and SF have been considered the main swimming coordination predictors (Seifert, Chollet, & Rouard, 2007), and a threshold to SF between 45 to 50 cycles·min^{-1} was also found (Pelayo et al., 2007; Potdevin, Bril, Sidney, & Pelayo, 2006; Seifert, Chollet, & Rouard, 2007) when the coordination switches from a catch-up to a superposition mode. This suggests that the higher the SF value, the greater the adoption of superposition coordination; the lower the SF, the greater the catch-up mode. In fact, in a movement, one or two control parameters could change the system in an abrupt way when a certain critical value is achieved (Kelso, 1984). Consequently, at that point, a coordination pattern that was stable becomes unstable, causing a sudden transition to a qualitative and stable coordination pattern as a self-organization result. Following this, using two different methods to analyze coordination, young swimmers performed a 50 m task in fifteen different ways (different speed and SF), showing that speed had a greater influence comparing to SF on coordination changes, at least with those speed and SF ranges (Silva et al., 2016).

In a 100 m front crawl race analysis, the fastest swimmers presented higher and stable SL and IdC values (Seifert, Chollet, & Chatard, 2007), corroborating with a similar analysis in IdC, but not in SL results (were similar in different skills; Ribeiro et al., 2016). In 400 m (Schnitzler, Seifert, & Chollet, 2009) and in 200 m pace (Alberty et al., 2005; Figueiredo, Pendergast, Vilas-Boas, & Fernandes, 2013), swimmers change the SL-SF ratio to maintain higher speeds, decreasing SL and increasing SF. Those variations could be explained by power losses due to fatigue, leading to decreases in strength production (Potdevin et al., 2006), expressed through the impulse per cycle reduction, raising IdC to maintain higher speed. Differences in SL and not in SF were also noticed when comparing elite swimmers with triathletes (Millet et al., 2002), proposing that high SL maintenance reflects swimmers' capacity to adopt efficient coordination (Schnitzler, Seifert, & Chollet, 2011). Thus, catch-up mode, which is usually considered a mistake, is useful for slow paces, as it favors glide mainly to deal with fatigue issues (Seifert, Chollet, & Rouard, 2007) and superposition is not a requirement for, but rather a high SF consequence (Seifert, Chollet, et al., 2004).

Representing instantaneous speed fluctuations, IVV reflects the application of forces acting on swimmers' body (Miller, 1975), suggesting that a greater propulsive organization could minimize it (diminishing negative acceleration between propulsions), increasing swim efficiency (Fujishima & Miyashita, 1998). Thus, as in speed, a great positive correlation between IVV and IdC was expected, but no correlation was found (e.g. Seifert, Toussaint, et al., 2010), with expert swimmers maintaining stable IVV while increasing IdC (Schnitzler, Seifert, Alberty, & Chollet, 2010; Schnitzler et al., 2009). In fact, IdC provides temporal information on the management of propulsive actions, but gives no information about the magnitude of the exerted forces and even less about the drag to overcome. This lack of correlation evidences a coordinative adaptation to maintain a lower energy cost with any other relation when y and z axes of motion were evaluated (Figueiredo, Toussaint, et al., 2013), highlighting that IVV does not depend on the coordination mode adopted, rather is influenced by several constraints (Newell, 1986; Sparrow & Newell, 1998), particularly by swimmers' specialization (sprint or long distance swimmer; Seifert, Komar, et al., 2010). Both variables provide complementary information, being relevant to differentiate skill level (Schnitzler et al., 2010).

2.2. Drag and breathing action

The relationship between IdC and drag was found to be quadratic, which was an expected result as drag increases with speed square (Toussaint & Beek, 1992), reflecting that swimmers have changed their upper-limb coordination mode (to superposition) to overcome higher active drag (Seifert & Chollet, 2010; Seifert et al., 2015). To achieve higher speed, swimmers have to produce great propelling force, but also they have to focus in minimizing drag (Toussaint, Carol, Kranenborg, & Truijens, 2006). Therefore, the optimum efficiency requires continuous force, i.e. no gaps between impulses and swimmers should perform high hand speed in a correct path during propulsion to develop high peak force (Toussaint & Beek, 1992), which could be a difficult task to novices. However, as the method often used to measure coordination (IdC) only presents temporal information, the relationship between IdC and propulsion remains unclear, as swimmers can slip the hand through water instead of generating greater propulsion, with studies reporting no statistical significant link between IdC and propelling efficiency (Seifert et al., 2015).

Despite not providing information about drag, few studies used materials that had influenced the observation of coordination adaptations. With two different parachute sizes no force increasing with raising speed was observed, as the overall force impulse has not changed significantly across pace (Schnitzler, Brazier, et al., 2011). As it implies an cycle adaptation (pull increasing while entry and catch phase decreasing), it was suggested that training with parachute could be an interesting tool to switch to superposition mode, while reducing SF and improving strength (Schnitzler, Brazier, et al., 2011). Paddles, which are artificial enlarged hands, allow swimmers to push off a larger mass of water, leading to decrease hand speed and SF, while raising propulsive phases. Although not significant, when using it, swimmers increased IdC with speed raising (Gourgoulis et al., 2009; Telles, Barbosa, Campos, & Andries, 2011). Conversely, wearing a wetsuit led to an increasing catch-up without modifying SF, recovery phase or lower-limb action (Hue et al., 2003a). Finally, when using semi-tethered swimming an IdC raising with increasing load and decreasing speed was observed, with a significant change at 2.84 kg, denoting swimmers' adaptations to higher drag, thus minimizing energy cost (Dominguez-Castells & Arellano, 2012), suggesting that it is a useful device to develop coordination.

In front crawl breathing implies body rotation, critical to speed and force implements (Keskinen & Komi, 1993), as it influences drag (Toussaint & Beek, 1992) and, consequently, swimmers' performance (Formosa et al., 2013). Moreover, as coordination is related to the management of propulsive phases, the relationship between swimming coordination and breathing analysis seems to be important, as propulsive discontinuity when breathing can be detected (Lemaitre et al., 2009; Lerda & Cardelli, 2003; Lerda, Cardelli, & Chollet, 2001). A ~3% difference in IdC values (both 100 and 800 m) was found when comparing swimming with and without breathing, with an increase in the propulsive phase duration (pull phase increased 2.23% when swimming without breathing; Lerda et al., 2001). At the end of an apnea training developed for three months (one hour apnea session, three times a week), a shorter SF and greater SL and IdC were observed (Lemaitre et al., 2009). These changes in the cycle organization were due to a shorter entry and catch and a longer pull phase. Thus, authors suggested that this training provides short race performance benefits for short races (50 m), enabling swimmers to better hold their breath and, consequently, a less disturbed cycle organization.

The asymmetric upper-limb coordination triggered by breathing (e.g. Formosa et al., 2014; Seifert, Chehensse, Tourny-Chollet, Lemaitre, & Chollet, 2008; Seifert, Chollet, & Rouard, 2007) results in a breathing laterality (preferential breathing side to a unilateral breathing pattern) and motor laterality (upper-limb dominance; Seifert, Chollet, & Allard, 2005). In fact, studies regarding upper-limb dominance led to hypothesize that, in front crawl swimming, one upper-limb is responsible for the swimming rhythm that probably produces higher forces (Tourny-Chollet, Seifert, & Chollet, 2009). According to Lerda and Cardelli (2003), the push phase occurs during the exhalation on the same side, enabling swimmers with unilateral breathing to associate propulsion and breathing, corroborating the direct relationship found between breathing laterality and force asymmetry (Broucek, 1993). Hence, it was suggested that the non-dominant upper-limb could be responsible for controlling and supporting inhalation, particularly by efficiently catching the water with the upper-limb extended in the front position (Seifert, Chollet, et al., 2005), meaning that catch-up coordination mostly occurred in the breathing and upper-limb dominance side, while showing superposition in the other side.

This coordination asymmetry was found to be greater in non-expert swimmers as the greater time spent inhaling led them to present a lag time between propulsions. Indeed, expert swimmers are characterized by a greater capacity to adapt their breathing to the biomechanical constraints produced by upper-limb propulsive actions (Lerda et al., 2001). However, differences between both upper-limbs were observed in different skill levels, suggesting that they were not related to expertise, but rather to a preferential breathing side (Seifert, Chollet, et al., 2005). The same authors proposed that the asymmetry may, thus, be a true coordinative mode and not just a functional error. Therefore, advertising swimmers to alternate the non-preferential side during training sessions could benefit upper-limb coordination symmetry (Seifert, 2010; Seifert et al., 2008).

3. How are physiological variables linked with swimming coordination?

Studies relating to physiological variables and coordination were mostly conducted in a 25 m maximal speed (10 studies and one in a 20 s swimming flume), in 25 m corresponding to a specific pace (21 studies) and in short distances (12.5, 30 and 50 m, with three, one and two studies, respectively), without considering fatigue effect. However, studies including mid distances (100 and 200 m, with 7 and 9 studies, respectively), different paces (one with 200, 300 and 400 m), long distances (three in 300 m and seven in 400 m) and a time limit trial (one study), allowed to observe that effect. As coordinative and biomechanical variables (e.g. mechanical and propelling efficiency and mechanical work) are related to energetic factors, while becoming fatigued, swimmers naturally adopt a movement pattern to achieve their goal, i.e. swim faster (Figueiredo, Morais, et al., 2013). Swimmers often have difficulties to finish the upper-limb movement of a cycle and start the next (Maglischo, 2003), leading to shorter SL, compensating with a progressively SF increasing (Alberty et al., 2008). In fact, at the same speed, elite swimmers are able to achieve longer SL while reducing SF, resulting in a more economical pattern (Pelayo, Sidney, Kherif, Chollet, & Tourny, 1996), hence pushing a great mass of water in a shorter time period thus explaining the higher speed and SL (Counsilman, 1971).

In a fatigued state , SF-SL combinations allow swimmers to modify their temporal upper-limb structure, decreasing non-propulsive phases, leading to consider that a rise in strength occurs (Alberty et al., 2009), but what really happens is a loss of efficiency (Figueiredo, Vilas-Boas, Seifert, Chollet, & Fernandes, 2010). Indeed, swimmers are unable to produce the same power with fatigue (Alberty et al., 2005), leading to longer propulsive phases, with IdC increasing (Alberty et al., 2003; Seifert, 2010). This is supported by a study that described an upper-limb angular velocity decrease due to fatigue, contributing to propulsive force reductions responsible for speed drops (Figueiredo et al., 2012). Therefore, the IdC modifications have not directly guaranteed better propulsion (Seifert, 2010), highlighting that the muscular endurance ability is one of the main limiting factors accounting for the high technical skill maintenance in severe exercises (Alberty et al., 2003). Swimmers' specialty should be also considered, as sprinters modify their coordination more than long-distance swimmers (presenting a greater catch-up; Alberty et al., 2008; Pelayo et al., 2007), as the former have more anaerobic training (presenting muscular fatigue sooner) and the latter aerobic training (highly focused on minimizing drag and maximize efficiency; Seifert, 2010). Hence, due to training specifications, higher hand speed and IdC was registered in swimmers comparing to triathletes (Seifert et al., 2016).

Defined as the total energy expenditure needed to displace the body over a given distance (di Prampero, 1986), energy cost was also considered determinant in front crawl coordination changes. Based on the fact that IdC depends on the timing between the actions responsible for the external work (Figueiredo, Toussaint, et al., 2013; Seifert, 2010), a positive relationship between energy cost and SF (Barbosa, Fernandes, Keskinen, & Vilas-Boas, 2008) and between SF and IdC (e.g. Seifert, Chollet, et al., 2004) explains the rising energy cost with increasing IdC (Figueiredo, Morais, et al., 2013; Seifert, 2010), although not confirming if superposition results in a more economic mode as suggested (Chollet et al., 2000). In fact, as opposition mode provides a greater propulsion continuity, it could lead to that assumption, but it cannot be neglected that IdC increases to overcome the greater drag resulting from speed raise. Consequently, swimmers have to increase their power output, raising energy cost. Catch-up mode represents an adaptation to constraints acting on the swimmer to reduce energy cost, by minimizing both propulsive and drag forces and keeping power losses from pushing water as low as possible, reflecting a greater SL (Toussaint & Truijens, 2005). Accordingly, energy cost is considered another constraint that influences motor organization development (Komar et al., 2012).

4. Do gender, skill level and maturation stage limit the coordination mode adopted?

All variables above discussed are greatly influenced by organismic constraints (Newell, 1986), i.e., swimmers' characteristics (as anthropometrics, gender, age and maturational stage), limiting the performers' movement solutions. In fact, greater anthropometrical characteristics and superior capacity to deal with fatigue were frequently associated with higher swimming skills. Furthermore, it is well known that differences between genders exist, with males often displaying a greater height, arm span, strength capabilities and with less fat mass comparing to female. These latter gender dissimilarities are developed during the maturational process, with considerable changes occurring during this period resulting in marked differences in swimmers' size and strength. Therefore, different swimming coordination adaptations were expected in these different groups.

4.1. Gender influence

When comparing different paces (switching from slower to faster – 3000 to 50 m), several studies showed an increasing in SF and a decreasing in SL associated with rises in IdC (e.g. Chollet et al., 2000; Seifert & Chollet, 2009; Seifert, Chollet, et al., 2004), but these changes do not occur with the same magnitude in both genders, tough. Notwithstanding SF has not significantly differed between elite men and women at every paces (Pelayo et al., 1996), SL and IdC were always higher in men, particularly in sprint races (Schnitzler et al., 2009; Seifert, Chollet, & Rouard, 2007). In addition, female swimmers always exhibited lower speed in all paces when comparing with males (e.g. Millet et al., 2002; Pelayo et al., 1996; Schnitzler, Ernwein, Seifert, & Chollet, 2006). The reason for those results could be linked to anthropometric characteristics, as female swimmers normally show lower height, arm span, foot and arm length.

Elite women tended to have similar adaptations as men, but they attained them only at maximal speed (Schnitzler et al., 2009; Seifert, Boulesteix, Carter, & Chollet, 2005; Seifert, Chollet, & Chatard, 2007). However, when normalizing swim speed, males displayed lower IdC (Schnitzler et al., 2009; Seifert, Boulesteix, et al., 2005), which could be related both to anthropometric characteristics and muscle power differences (Seifert, Boulesteix, et al., 2004). Indeed, females' smaller mechanical power output, lower drag (Toussaint et al., 1988) and height and arm span lead them to compensate their shorter SL by changing upper-limb coordination, presenting a greater catch-up to achieve the same swim pace as men (Schnitzler et al., 2009; Seifert, Boulesteix, et al., 2005). As a matter of fact, female swimmers are less efficient as they had shorter SL and a lower swimming speed at the same level of muscle activation (Rouard & Billat, 1990), showing only one peak force due to fatigue (Seifert, Boulesteix, et al., 2004). Conversely, the higher SL showed by men drove them to produce more force to overcome the drag associated to their higher speed. Therefore, elite men could increase their propulsive phases more than women, since they are able to apply two peak forces instead of one (Maglischo, 2003).

Furthermore, it was also suggested that the lower fat distribution presented by men (Seifert, Chollet, & Rouard, 2007) could also influence their higher IdC values. In this sense, catch-up coordination observed in female swimmers should not be characterized as a bad coordination (Schnitzler et al., 2009; Seifert, Boulesteix, et al., 2005). In fact, women were not able to switch to superposition with the increasing swimming speed, remaining in catch-up mode in opposition to men, who increased their IdC through decreasing in entry and catch phase and increasing in pull, push and recovery phases (Chollet et al., 2000; Keskinen & Komi, 1993; Lerda et al., 2001). This inability to switch to superposition coordination mode was probably due to their slower swimming speed, as they could not reach the 1.8 $m \cdot s^{-1}$ threshold (Seifert, Chollet, et al., 2004) and, consequently, due to the fact that they had to overcome a smaller resistance, comparing to males (Kolmogorov & Duplishcheva, 1992).

4.2. Skill level and maturation stage

Skill is the ability to solve one specific motor problem. It is not a movement formula of permanent muscle forces imprinted in some motor center (Bernstein et al., 1996). The same authors argued that to achieve a good performance level learners must perform many times to experience all sensations allowing to construct the basis for their sensory corrections. Yet, this does not mean that only with repetition swimmers will become experts/skilled performers. Likewise, performance level should not be classified only by the final result (final score), since the same result could be accomplished by distinct motor organizations. Nevertheless, in swimming research the speed the swimmer can attain, usually defines its skill level. Therefore, this review followed this rational, classifying higher skill level swimmers, who have showed the best race time. In fact, one of the main swimming studies concern is to identify which variables best predict and better explain swimming performance. Following this, studies have been done aiming to compare swimming coordination between lower and higher level swimmers (e.g. Matsuda, Yamada, Ikuta, Nomura, & Oda, 2014; Nikodelis et al., 2005; Seifert, Chollet, & Chatard, 2007) and to analyze young swimmers' coordination (e.g. Silva et al., 2012a; Silva et al., 2016; Strzala, Tyka, & Krezalek, 2007).

Higher IdC values have been reported when comparing elite to lower level swimmers (e.g. Chollet et al., 2000; Lerda & Cardelli, 2003; Millet et al., 2002) and, as in women, this could be related to lower speed and SF values achieved, remaining in almost cases in catch-up mode, even in the fastest races. However, these results could be more related to a poor technique rather to lower anthropometric characteristics as in women (Seifert, Chollet, & Rouard, 2007). These IdC values could also reflect that elite swimmers are focused in adopting a streamlined position as they have a higher drag to overcome, due to the greater speed they achieved at the same SF. Conversely, it has also been shown that for the same speed elite and lower level swimmers adopted different SF, highlighting a worse water movement performed by low level swimmers that implement less effective propulsion. In addition, when comparing triathletes and elite swimmers, it was noted that the former could not reduce the recovery phase at maximal speeds (among the three fastest races, between 80 and 100% of maximal speed), confirming that only the best swimmers can reduce this upper-limb phase (Millet et al., 2002).

More recently, the concept of variability as a distinguishing performance characteristic has been analyzed (e.g. Bideault, Herault, & Seifert, 2013; Seifert, 2010; Seifert et al., 2014b). Although expertise has been characterized as the capacity to produce the same movement as an automatic action (Ericsson, Krampe, & Tesch-Römer, 1993), considering variability as noise (Glazier et al., 2006), it was argued that higher skill levels could not be characterized with a specific profile, as variability in human behavior occurs at many levels in the training process (Bideault et al., 2013). Therefore, it was suggested that variability could correspond to a functional aspect, reflecting a greater swimmers' adaptation, as there is no optimal coordination pattern (Seifert et al., 2014b). Following this, it was hypothesized that skilled swimmers benefit from more flexible motor solutions (Dadashi et al., 2015), however, further studies should be conducted regarding this topic.

When observing young swimmers, contradictory results have appeared in literature, with some studies stating they only adopt catch-up coordination even at high speeds (Fernandes et al., 2009; Silva et al., 2012b; Silva et al., 2014) and others noticing superposition mode (Schnitzler, Seifert, Chollet, & Toussaint, 2014; Strzala et al., 2007). However, in those latter studies, swimmers are older (~ 13 vs. 16 years of age), suggesting that maturation could be essential to allow them to achieve higher IdC values. In fact, anthropometric characteristics are considered the most important factor contributing to young swimmers' performance (Figueiredo, Silva, Sampaio, Vilas-Boas, & Fernandes, 2015). When comparing different maturation stages (Silva et al., 2012b), a trend to achieve higher IdC values in post-pubertal swimmers has been observed compared to pubertal swimmers. Using another approach and comparing young with elite swimmers (Nikodelis et al., 2005), no differences were recorded in the coupling strength between hands, although elite swimmers showed more consisted and symmetrical hand trajectories, especially in the fastest races. These results evidence the importance to conduct further research using dynamical analysis and with interventional studies, to observe the main characteristics and developments in youth coordination.

Conclusion

The majority of swimming coordination analyses has been using kinematic methods (mainly based on temporal dimension), thus existing a scarcity in spatial-temporal and force information research. It was concluded that inter-limb coordination does not automatically reflect propulsion, as part of the motor organization may be spent floating and breathing. Furthermore, although upper-limbs generate a huge part of the propulsion in front crawl technique, only one study analyzed the lower and upper-limbs coordination. Speed and SF are the main influencing parameters, suggesting they are control parameters, although the other biomechanical (SL, IVV and drag), physiological (fatigue and energy cost) and swimmers' characteristics (gender, skill level and age) exert a combined influence on coordination. Therefore, it has been inferred that there is not an optimal coordination pattern to a given motor problem, but several solutions exist. Consequently, there is no "ideal" coordination pattern, due to the fact that coordination depends on the relations among interacting constraints (task, environment and organismic).

Chapter 3.

Task constraints and coordination flexibility in young swimmers

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Submitted for publication on Research Quarterly for Exercise and Sport.

Abstract

Purpose: This study aimed to examine young swimmers behavioural flexibility when facing different task constraints such as swimming speed and stroke frequency. Method: Eighteen 13-15 years old competitive swimmers performed 15x50m front crawl (with 5 min interval), five trials at each 100, 90 and 70% of their 50m maximal swimming speed, randomly at 90, 95, 100, 105 and 110% of their preferred stroke frequency. Seven aerial and six underwater cameras were used to assess kinematics, with upper limb coordination computed through continuous relative phase (allowing extracting the relative times spent in in-phase, anti-phase and out-of-phase) and index of coordination methodologies. A cluster analysis detected the different patterns of coordination used by swimmers. Result: Six different clusters were found, confirming that speed and stroke frequency act as the main constraints to develop behavioral flexibility of young swimmers. Conclusion: It was confirmed that not all the variability is functional, i.e., the patterns nature and appropriately shifting between them (according to speed and stroke frequency) seem more important than attain the highest number of changings or patterns (range of the repertoire).

Key words: Swimming, ecological dynamics, biomechanics, adapatability.

Introduction

It is well accepted that a high level of expertise is characterized by motor dexterity, expressing the expert's ability to reach the goal of a task correctly, quickly, reasonably (efficiently) and with resourcefulness (Bernstein, 1996). Resourcefulness (i.e., the initiative and stability to a set of constraints) appears as the most important property of dexterity, as this latter does not refer to the movements themselves, but to their adaptation to a set of constraints. In fact, following the ecological dynamics theoretical framework, the successful performer is able to adapt his/her behaviour to dynamically shifting environments that characterize sport competition (Seifert, Button, & Davids, 2013), with resourcefulness reflecting his/her capability to functionally vary behaviour, either by switching between coordination patterns or by displaying its superficial spatial-temporal adjustments, to reach the task-goal without performance outcome deterioration (Seifert et al., 2013). Therefore, although behavior could be characterized by stable and reproducible coordination patterns against perturbations, it is not stereotyped and rigid but flexible and adaptive (Warren, 2006).

Adaptive behaviour does not consist in coordinated movement per se but in goal-directed environment orientated action. The ecological dynamics framework postulated for individual-environment system coupling, in which information is viewed as regulating action directly, supporting circular causality between perception and action (Davids, Araújo, Hristovski, Passos, & Chow, 2012). Thus, "*the function of perception and action is to stabilize behavior on the goal for a given task while maintaining adaptive flexibility*" (p. 358, Warren, 2006), meaning that to avoid getting locked into a rigidly stable solution, performer also uses information to maintain adaptive flexibility to cope with a set of constraints and to satisfy the task goal.

Newell (1986) proposed to manipulate three types of constraints, which act as boundaries for the perceptual motor workspace exploration, instead of using prescriptions: (i) organismic, referring to the structural or functional ones; (ii) environmental (external to the organism), referring to environmental characteristics; and (iii) task, related to the goal of the activity, the rules or instructions specifying response dynamic and the implements or machines specifying response dynamic. Constraints are used as boundary conditions limiting the action possibilities and the coordination patterns available, interacting in complex configurations, shaping the perceptual-motor workspace of each learner (Davids et al., 2012). Therefore, it has been argued that skill adaptation (rather than its acquisition) can be guided through the manipulation of the key constraints acting on the task (Newell, 1986), with speed and stroke frequency found to be the main constraints in coordination in cyclic locomotion tasks (e.g. Kelso, 1995).

In swimming, especially in front crawl, speed and stroke frequency appear as the main constraints on upper limb coordination (Potdevin, Bril, Sidney, & Pelayo, 2006; Seifert, Chollet, & Rouard, 2007), with a quadratic regression observed between the increase of speed and the change of the upper limb coordination (Seifert & Chollet, 2010). Moreover, expert swimmers usually switch from a catch-up to a superposition upper limb coordination pattern up to a speed of ~1.80 $m \cdot s^{-1}$ and/or a stroke frequency of ~50 $cyles \cdot min^{-1}$ (Seifert, Chollet, & Bardy, 2004). This observation was confirmed by detecting a threshold, above which the front crawl swimmers change their upper limb coordination from the catch-up pattern to the superposition pattern occurred at a stroke frequency between 45 and 50 $cyles \cdot min^{-1}$ for non-expert and between 50 to 55 $cyles \cdot min^{-1}$ for expert swimmers (Potdevin et al., 2006).

Moreover, at higher speeds, active hydrodynamic drag also increase (Toussaint & Truijens, 2005) influencing upper limb coordination, as the impulse to move forward has to be higher, raising necessarily time spent in propulsive phases. Hence, at a constant speed, stroke frequency increases to generate more propulsion, as the development of fatigue leads to a reduced force generating capacity (Alberty, Potdevin, Dekerle, Pelayo, & Sidney, 2011). In fact, studies showed that coordination is very dependent on interacting effect of changes in stroke frequency (e.g. Alberty et al., 2008) and skill level (e.g. Seifert, Chollet, et al., 2007). However, it was found that expert swimmers try to compensate the stroke length reduction by increasing stroke frequency as a strategy to limit the decrease in their speed during a race (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011). Thus, manipulating stroke frequency during paced exercise helps to stabilize swimmer's motor organization (Alberty et al., 2008). Nevertheless, training swimmers to perform at different stroke frequencies to enlarge their behavioural adaptability is not a common coaches strategy, as they often try to stabilize a given stroke frequency that swimmers should keep stable along the event. In fact, competition analysis showed that stroke frequency can really vary within and between laps, inviting us to consider and manipulate speed and stroke frequency since they showed to be the main constraints to evidence a certain coordination pattern.

The constraint-led approach could be particularly meaningful for young swimmers who have not yet stabilized a certain stroke frequency and upper limb coordination pattern, notably due to changes in strength and body size with age. In fact, changes in muscle development in young swimmers influence muscle length-tension and force-velocity relationships, which could improve swimmers performance (Nasirzade et al., 2014). Complementarily, the increase in anthropometrical characteristics during growth has been indicated to be the main reason for performance changes through its influence in biomechanical parameters (e.g. stroke length increases; Nasirzade et al., 2015). In fact, these modifications are related to the maturation process that tends to begin at age 8–10 years in girls and 10–12 years in boys, reaching its end ~14 years (Malina, Bouchard, & Bar-Or, 2004).

The main aim of the current study was to examine young swimmers behavioural flexibility (through upper limbs coordination) when task constraints (speed and stroke frequency) are manipulated, investigating the relevance of training around swimmer's preferred stroke frequency to enlarge his/her behavioural flexibility. We hypothesized that high behavioural flexibility might correspond to (i) a great repertoire of upper limb coordination pattern, allowing swimmers to switch between coordination patterns, and (ii) a high stability of upper limb coordination pattern within a speed range (slow *vs.* fast speed) and/or stroke frequency (low *vs.* high stroke frequency). Complementarily, it was examined the inter-individual coordination variability to cope with the above-referred task constraints, and we hypothesized that some swimmers might be more sensitive to stroke frequency effect, others might change their upper limb coordination pattern with swimming speed and some might display upper limb coordination pattern changes in relation to a combined effect of stroke frequency and swimming speed.

Methods

Participants

Eighteen young swimmers (5 boys and 13 girls) participated in this study. Their main characteristics were: 14.8 ± 0.4 vs. 13.6 ± 0.8 years old, 175.0 ± 7.2 vs. 163.2 ± 5.7 cm of height, 177.9 ± 7.3 vs. 166.2 ± 5.7 cm of arm span, 68.3 ± 4.1 vs. 56.1 ± 6.5 kg of body mass and 9.0 ± 2.2 vs. 7.9 ± 3.0 years of practice (for boys and girls, respectively). All participants were in the same skill level as they integrated the same competition stage. Hence, these swimmers did not receive any specific training focusing on stroke frequency prior to the current study but they were familiar with the metronome for stroke frequency pacing. An informed consent was signed by swimmers' parents and coaches well knew the experimental protocol. Swimmers were informed about the experimental procedures, which were approved by the local ethics committee and performed according to the Declaration of Helsinki.

Experimental procedure

After a standard warm-up (where swimmers could familiarize themselves with the metronome), each participant performed 15 x 50 m front crawl, with in-water starts, in a 25 m indoor heated 1.90 m deep swimming pool without breathing in the centre of the pool, to avoid the breathing effect on coordination, each swimmer performed five 50 m trials at 100, 90 and 70% of their 50 m maximal speed, being accepted 2.5% of variability along the different strokes. Between each 50 m trial swimmers rested 5 min, so that fatigue did not influence their performance. Bouts 1-5, 6-10 and 11-15 were performed randomly at 90, 95, 100, 105 and 110% of their preferred stroke frequency, which was calculated in the middle of the pool, between three consecutive upper limb cycles, using a stop-watch. To contemplate possible variations during the 50 m swims, stroke frequency was calculated in both 25 m laps of the 50 m bouts (and used the average values). At each swimming speed, the first repetition aimed to determine swimmers preferred stroke frequency, reason why only a visual pacer was used in this trial, placed in the bottom of the pool with a flash every 5 m (Pacer2Swim OEM Kulzer TEC, Aveiro, Portugal). When swimmers did not performed at the target speed and stroke frequency, which was monitored using an underwater metronome was placed inside the swim cap near the ear (Tempo Trainer Pro, Finis®), the trial was repeated.

Apparatus

To record swimmers performance, a 13-camera dual-media motion capture (MoCap) setup was used, with seven land plus six underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 100 Hz. The calibrated volume was defined using underwater, above water and twin system to merge the first and the latter calibrations (according to the manufacturer's guidelines). This enabled the creation of 3D dual-media working volume, where the orthogonal axes were defined as x, y, z for horizontal, medio-lateral and vertical (z = 0 defines the water surface) movements (respectively). Data acquisition was performed with Qualisys Track Manager Version 2.7 (Qualisys AB, Gothenburg, Sweden), with swimmers using ten anatomical reflective landmarks on the shoulders, elbows, wrists, mid fingers and hips, enabling to digitize frame-by-frame using the Qualisys software. The data treatment was performed with the same system, by identifying manually the different anatomical points.

Data processing

Stroking parameters

Although swimming speed and stroke frequency were controlled during the entire test, it were also calculated after the digitizing process, with the former assessed through the horizontal displacement of the hip during one upper limb cycle over its total duration and the latter as the result of the inverse of the time needed to complete one upper limb cycle (defined as two consecutive water entries of the same hand). Stroke length was also obtained by the horizontal displacement of the hip through one upper limb cycle.

Upper limb coordination analysis

Coordination between right and left upper limbs was assessed through the continuous relative phase (CRP) that has been considered appropriate for cyclic and sinusoidal signals (Lamb & Stöckl, 2014). Its assessment between the upper limbs (arm-shoulder-trunk angle) was performed for one single cycle (Figure 1) during the 50 m front crawl recorded in the central part of the pool to avoid the start, turn and breathe effects. Cycle duration was expressed in percentage allowing its comparison. As CRP was typically derived from the position-speed phase-planes of two predominantly sinusoidal oscillators, it contain spatial and temporal information, enabling angular velocities computation from positional data for left and right body sides. Widely used in human movement coordination, phase portraits were computed after normalization (Fuchs, Jirsa, Haken, & Kelso, 1996), with the zero value considered to be arbitrary, i.e., without any qualitative meaning (Lamb & Stöckl, 2014), and with the amplitude differences between the oscillating segments not affecting coupling measures (Kurz & Stergiou, 2002). Angular displacements and angular velocities were normalized (θ_{norm} and ω_{norm}, respectively) in the interval [-1, +1] as follows (Kurz & Stergiou, 2002; Lamb & Stöckl, 2014):

$$\theta_{norm} = \frac{2\theta}{\theta_{max} - \theta_{min}} - \frac{\theta_{max} + \theta_{min}}{\theta_{max} - \theta_{min}}$$

where θ_{max} and θ_{min} are the maximum and minimum angular positions within one complete upper-limbs cycle, respectively.

$$\omega_{norm} = \frac{2\omega}{\omega_{max} - \omega_{min}} - \frac{\omega_{max} + \omega_{min}}{\omega_{max} - \omega_{min}}$$

where ω_{max} and ω_{min} are the maximum and minimum angular velocity within one complete upper limbs cycle, respectively.

Although some authors presented the CRP results without any normalization in the phase angle, Kurz and Stergiou (2002) highlighted differences when conducting normalization or not. Therefore, the following reference phase angle was used:

$$\emptyset = tan^{-1}\,(\omega_{norm}/\theta_{norm})$$

CRP was found through the subtraction of the phase angle between oscillators at each time point time over the entire cycle (i.e. the left shoulder phase angles were subtracted from the right ones – Figure 2). CRP values can range from 0º to 360º and three different modes could be found: (i) in-phase (0º), when it is observed a synchronization between the upper limb actions; (ii) anti-phase (180º), when an opposite action is observed; and (iii) out-of-phase, when there is a lag time between the two upper limb actions. Nevertheless, as a variation of ± 30° was accepted for the determination of a coordination pattern (Bardy, Oullier, Bootsma, & Stoffregen, 2002; Seifert, Delignieres, Boulesteix, & Chollet, 2007), an in-phase occur when CRP vary between 0º ± 30º or 360º ± 30º (i.e. when 330º < CRP < 30º), an anti-phase is considered when their parameters ranges between 180º ± 30º (i.e. when 150º < CRP < 210º) and the out-of-phase is observed when the CRP assumes values outside the above referred ranges (i.e. when 30º < CRP < 150º and 210º < CRP < 330º).

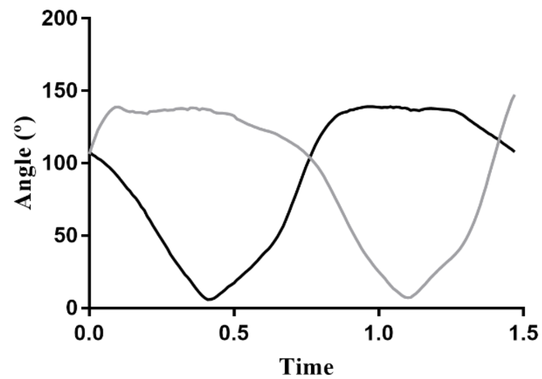


Figure 1. Continuous relative phase between the right (grey line) and left (black line) upper-limbs (arm shoulder-trunk angle) during a cycle.

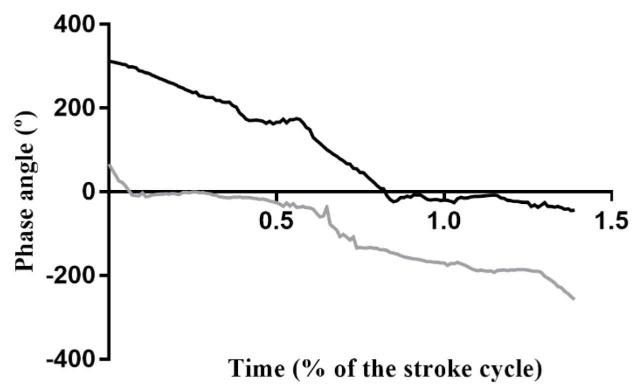


Figure 2. Phase angle for right (grey line) and left (black line) side.

According to Seifert et al. (2011), different parameters were extracted to examine the coordination between upper limbs and its variability within cycle: (i) the mean CRP and its variability through the standard deviation of CRP over a cycle; (ii) the relative time spent in in-phase, out-of-phase and in anti-phase (all expressed in %) to inform about the coupling between upper-limb coordination (and not propulsive action coupling); and (iii) the relative time between two propulsive upper limbs actions, corresponding to the IdC (Chollet, Chalies, & Chatard, 2000) – the time between the beginning of propulsion of the first right and the end of propulsion of the first left upper-limb cycles, and between the beginning of propulsion of the second left upper-limb cycle and the end of propulsion of the first right upper-limb cycle.

Three different synchronization modes are possible to identify in front crawl: (i) opposition (IdC = 0%), when one upper-limb begins the propulsive phase and the other is finishing it, providing continuous motor actions; (ii) catch-up (IdC < 0%), existing a lag time between propulsive phases of the two upper-limbs; and (iii) superposition (IdC > 0%), describing an overlap in the propulsive phases of both upper limbs.

Statistical analysis

Cluster analysis has been widely used to examine movement and coordination pattern variability, and, as no a priori assumptions regarding dataset structure (e.g. the normality of the distribution) are required to identify similar patterns (Duda, Hart, & Stork, 2001), it is an interesting technique to detect coordination patterns. Furthermore, as this process is an unsupervised machine learning (Duda et al., 2001), it organizes groups without human intervention and inherent bias, it identifying homogeneous individuals clusters that share several common characteristics. Given that, a cluster analysis examined changes in behavioural patterns and determined the presence of upper limb coordination variability, identifying the presence of potential groupings within the whole set of individuals regarding swimming speed and stroke frequency. Clustering was performed on six kinematic parameters, each of them relating to upper limb coordination (mean CRP, SD of CRP, time spent in in-phase, in out-of-phase and in anti-phase, and IdC) for each bout, so that natural groupings could be observed. The rationale used was based on our first goal, which aimed to identify the nature of the coordination by using mean CRP over the cycle. However, as already mentioned by Figueiredo, Seifert, Vilas-Boas, and Fernandes (2012), we expect that the swimmers did not exhibit the same upper limb coupling all along the cycle. Therefore SD is the second indicator that can indicate any fluctuation of relative phase. Then, to go deeper in the nature of the upper limb coupling, we have quantified the time spent in each pattern of coordination (in-phase, anti-phase, out-of-phase). Finally, those previous indicators did not inform on the coupling between the propulsive actions but only on the coupling between joints; therefore, our second goal was to include IdC (Chollet et al., 2000).

The Bayesian Information Criterion index was used as a model-selection criterion to validate the number of clusters found within the data set. It was performed for 2 to 12 potential number of clusters and represented in a vector containing the above referred index for the number of clusters, corresponding to the first local maximum that best fitted the data set (i.e., the number representing the highest ratio between inter- and intra-cluster distances; Ludden, Beal, & Sheiner, 1994). The cluster analysis ran once for the entire data sets, comprising 270 trials (18 swimmers * 3 speeds * 5 conditions of stroke frequency) using the Fisher-EM algorithm (Bouveyron & Brunet-Saumard, 2014), based on a probabilistic model that projects the data in a latent subspace at each iteration in such a way that emerging clusters maximize the Fisher information (i.e. maximizing the inter-cluster while minimizing the intra-cluster distances). Finally, regarding the cluster validation, it was calculated sparsity, which enables to select discriminative variables among the set of original parameters. Indeed, when dealing with high-dimensional data that a large number of noisy or non-informative variables are present in the set of the original parameters. The use of Fisher-EM algorithm simultaneously clusters the data and produces a low-dimensional and discriminative subspace representing the data (Bouveyron & Brunet-Saumard, 2014). When the sparsity is close to 1 it means that the parameter is informative, whereas a score of 0 indicates that the parameter is low informative. All statistical procedures were performed with RStudio© (0.99.491, 2009-2015, RStudio, Inc).

Results

Behavioural profile according to speed and stroke frequency

The sparsity values were 0.81 for CRP, 0.98 for standard deviation of CRP, 0.97 for the time spent in in-phase, 0.92 for the time spent in out-of-phase, 0.98 for the time spent in anti-phase and 0.88 for IdC suggesting that these six parameters were informative to cluster our 270 observations. Six different clusters were distinguished as follows (Table 1): (i) cluster 1 (composed by 16 observations) displayed a slower speed, stroke frequency and IdC, with a greater relative time in in-phase pattern; (ii) cluster 2 (included 99 observations) showed intermediate speed and IdC values, and lower standard deviation of CRP, although a high relative time in anti-phase pattern; (iii) cluster 3 (with 17 observations), although showing a slower value of speed and more 50 m trials with the second highest value of stroke frequency, it displayed the second highest value of IdC, with lower CRP and time percentage in anti-phase (as this cluster presented the highest value of out-of-phase); (iv) cluster 4 (with only 5 observations) showed high CRP, standard deviation of CRP and relative time spent in in-phase pattern, although presenting the lowest value of IdC; (v) cluster 5 (with 107 observations) showed the highest speed, stroke frequency and IdC values of all clusters, but a lower relative time spent in in-phase; (vi) cluster 6 (with 26 observations) expressed an intermediate speed value, with a quite low stroke frequency and with intermediate values of CRP and standard deviation of CRP comparing to other clusters.

Table 1. Mean ± SD values of each cluster regarding speed, stroke frequency, mean of continuous relative phase (CRP), standard deviation of continuous relative phase (SD of CRP), relative time in in-phase, anti-phase and out-of-phase, and the index of coordination (IdC).

	Cluster 1 (n = 16)	Cluster 2 (n = 99)	Cluster 3 (n = 17)	Cluster 4 (n = 5)	Cluster 5 (n = 107)	Cluster 6 (n = 26)
Speed ($m \cdot s^{-1}$)	1.09 ± 0.14	1.25 ± 0.20	1.14 ± 0.12	1.21 ± 0.21	1.42 ± 0.17	1.26 ± 0.24
Stroke frequency ($cycle \cdot min^{-1}$)	34.3 ± 8.5	38.1 ± 8.0	41.7 ± 5.9	34.2 ± 9.1	44.0 ± 8.7	36.8 ± 11.5
CRP (º)	226.4 ± 10.0	195.4 ± 12.5	183.0 ± 16.8	256.0 ± 25.2	190.3 ± 12.0	227.0 ± 9.8
SD CRP (º)	74.8 ± 11.1	44.2 ± 11.6	68.8 ± 15.0	115.8 ± 21.9	47.5 ± 7.4	66.2 ± 11.8
In-phase (%)	6.9 ± 4.9	1.7 ± 1.9	1.8 ± 1.7	5.6 ± 5.3	0.8 ± 0.8	4.9 ± 2.9
Anti-phase (%)	63.7 ± 7.9	64.2 ± 7.5	22.6 ± 7.0	41.7 ± 8.4	43.6± 7.1	39.4 ± 7.1
Out-of-phase (%)	29.4 ± 4.9	34.1 ± 7.1	75.6 ± 7.8	52.7 ± 8.9	55.7 ± 7.2	55.7 ± 7.4
IdC (%)	-12.0 ± 7.3	-10.2 ± 5.3	-9.6 ± 4.5	-14.5 ± 4.3	-9.1 ± 5.1	-12.0 ± 5.7

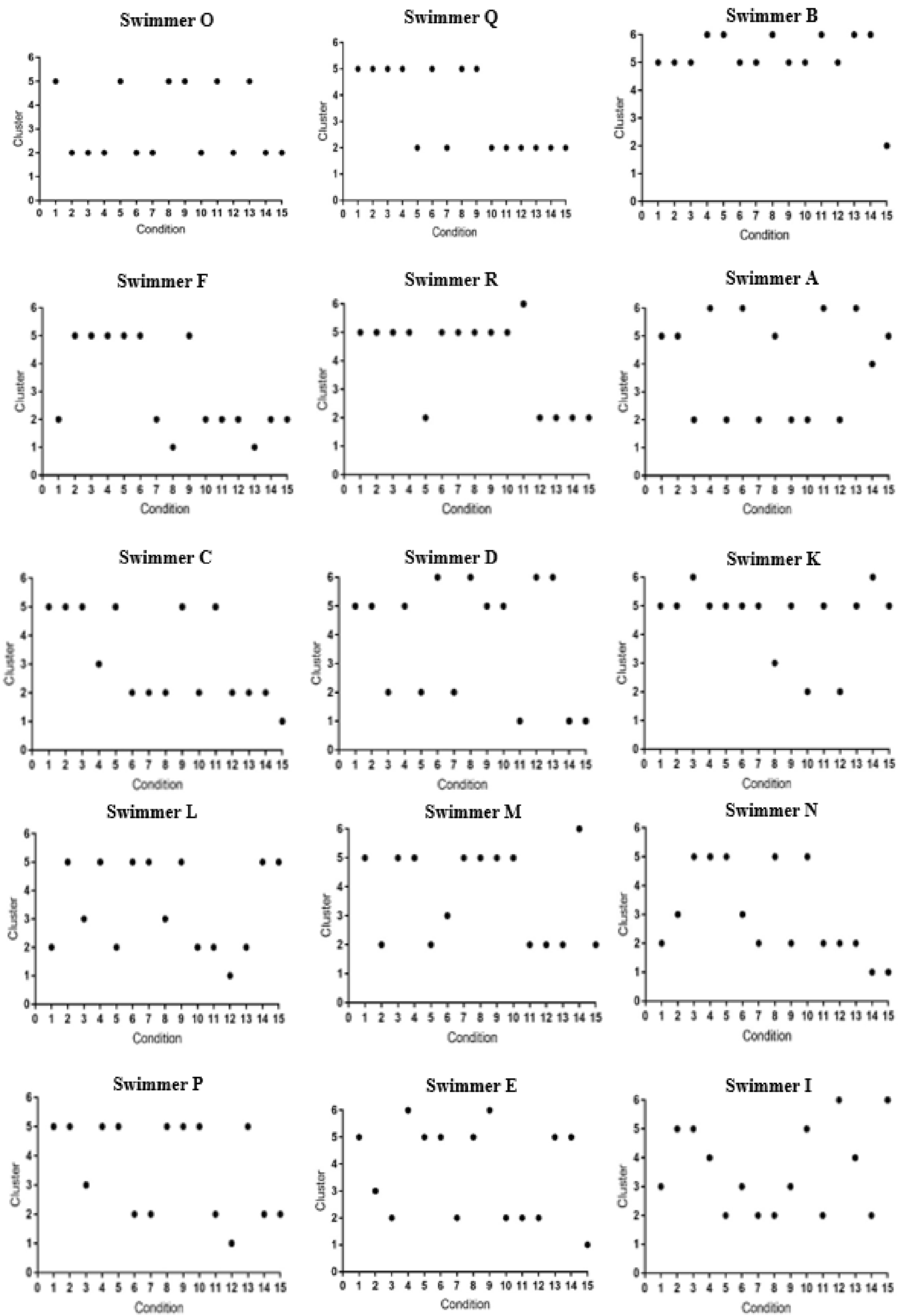
Table 2 shows the clusters distribution considering each speed and stroke frequency condition without considering inter-individual variability.

Table 2. Percentage of occurrence of the different clusters that occurred for each swimmer within a stroke frequency condition.

Speed	Stroke frequency	Cluster 1 (n = 16)	Cluster 2 (n = 99)	Cluster 3 (n = 17)	Cluster 4 (n = 5)	Cluster 5 (n = 107)	Cluster 6 (n = 26)
100%	90%	0	5.1	11.8	0	10.4	0
	95%	0	5.1	11.8	0	10.4	0
	100%	0	4.0	17.6	0	9.3	3.8
	105%	0	2.0	5.9	40	9.3	11.6
	110%	0	7.1	5.9	0	8.4	3.8
90%	90%	0	6.0	17.6	0	6.5	7.7
	95%	0	12.1	0	0	4.7	3.8
	100%	6.3	2.0	17.6	0	9.3	7.7
	105%	0	3.0	11.8	0	11.2	3.8
	110%	0	10.1	0	0	7.5	0
70%	90%	25	8.1	0	0	2.8	11.6
	95%	12.5	12.1	0	0	0.9	11.6
	100%	12.5	6.1	0	20	3.7	19.2
	105%	12.5	9.1	0	40	1.9	11.6
	110%	31.2	8.1	0	0	3.7	3.8

Inter-individual behavioural variability

Figure 3 shows the cluster distribution considering each condition of speed and stroke frequency for each swimmer. The majority of young swimmers (n = 8) switched between four clusters in the different conditions imposed by the 15 x 50 m test. It was also observed that switching three and five times between clusters was the second mostly used profile (n = 3 each). Only two swimmers switched between the six clusters and between two clusters. It was also noticed that swimmers with greater speed and stroke frequency variation between trials switched between clusters 3 and 6.


Swimmer O
Swimmer Q
Swimmer B
Swimmer F
Swimmer R
Swimmer A
Swimmer C
Swimmer D
Swimmer K
Swimmer L
Swimmer M
Swimmer N
Swimmer P
Swimmer E
Swimmer I
Cluster
Condition

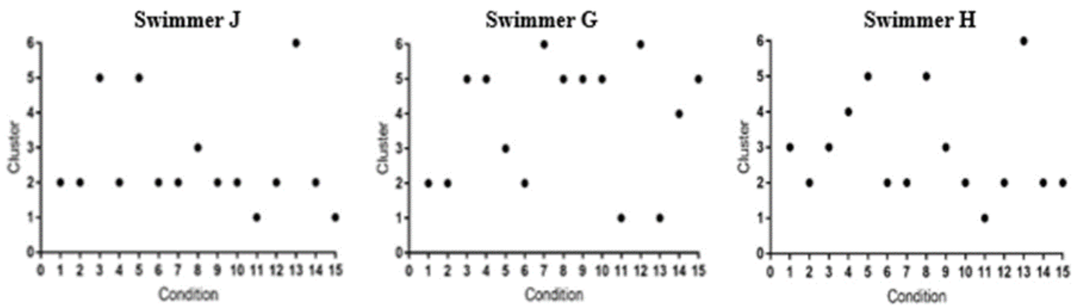


Figure 3. Clusters distribution through the 15 different conditions (with sequence presented on table A.2., stating with speed 100% and 90% of preferred stroke frequency and finishing with 70% of speed and 110% of preferred stroke frequency) displayed by swimmers with: two clusters adopted (O and Q), three (B, F and R), four (A, C, D, K, L, M, N and P), five (E, I and J) and six (G and H).

Discussion

Behavioural profile according to speed and stroke frequency

Cluster analysis showed different behavioural dynamics when speed and stroke frequency were manipulated, confirming that these two parameters seem to act as the main constraints influencing the system behaviour (Kelso, 1995). Indeed, although a catch-up mode of coordination between propulsive phases of upper limbs was always observed, six different clusters emerged through the various ranges of speeds and stroke frequencies imposed by the experimental protocol. The existence of catch-up coordination mode, even at the fastest speeds, was in accordance with the literature for young swimmers (e.g. Figueiredo, Silva, Sampaio, Vilas-Boas, & Fernandes, 2015; Silva et al., 2012). Our main findings (summarized in tables 1 and 2) highlighted that cluster 1 and 5 seemed to be functional behaviours and complemented each other, as cluster 1 was mainly used at lower speeds, while cluster 5 was mostly adopted the maximal and sub-maximal (100 and 90% speed, respectively) conditions, whatever the stroke frequency. The four other clusters represent mixed strategies, combining speed and stroke frequency differently.

Cluster 1 included 50 m bouts mainly performed at 70% maximal speed, where the stroke frequency seemed to have not exerted a preponderant effect, as it contained similar number of 50 m repetitions at different percentages of stroke frequencies (confirmed in the tables). Indeed, in this cluster, the speed (relative and absolute) and stroke frequency presented the lowest values. Consequently, a lower IdC, with the highest value of relative time in in-phase pattern was exhibited, which is appropriated for slow paces since it favours the glide phase mainly for buoyancy reasons (Seifert et al., 2004). Indeed, although swimming locomotion results in both the ability to produce propulsive forces and minimize the resistive ones (Toussaint & Truijens, 2005), it is known that swimmers favour propulsion generation at sprint paces, giving great importance to active drag minimization at slowest paces (McCabe & Sanders, 2012). This resistance minimization includes a great glide phase, where swimmers search for an efficient hydrodynamic position, confirming the catch-up mode of coordination.

Cluster 5 represented the most frequent pattern adopted by swimmers, with speed and stroke frequency effect appearing to be combined, as all stroke frequency conditions were present in the trials swam at 90 and 100% of swimmers 50 m maximal speed. Regarding CRP values, the out-of-phase coupling was the most dominant pattern (~55% of the cycle duration), while the time spent in in-phase pattern was the lowest. Cluster 5 exhibited the highest IdC value (although remaining negative), expressing a catch-up coordination pattern. As ages between 11 to 14 years old are characterized as a period of versatility for mastering the technique and to preparing for a progressive workout Sozañski (1999), it could explain why young swimmers could not achieve the same upper limb coordination pattern than adult elite swimmers, who adopt opposition or even a superposition coordination pattern when performing at maximal speeds (e.g. Chollet et al., 2000).

As suggested previously, the four other clusters showed mix strategies with various combinations of speed and stroke frequency conditions. For instance, cluster 3 included trials swam at maximal and sub-maximal speeds (100 and 90%) and low stroke frequencies (varying between 90 and 100%). However, when comparing to other clusters, this did not show the highest speed values, presenting the second lowest speed and the second highest stroke frequency values (Table 1). Moreover, regarding the absolute speed value, it was expected to display very negative IdC values but, comparing to other clusters, it presented the second highest IdC value. Therefore, although this cluster expressed a lower speed and stroke frequency (in absolute) comparing to others, its IdC value remained high (the second highest), showing that the combination of high speed and stroke frequency could play an important role. In the literature, positive correlations between IdC with speed (e.g. $r = 0.37$ Lerda & Cardelli, 2003; $r = 0.69$ Seifert et al., 2004) and stroke frequency (e.g. $r = 0.54$, Chollet et al., 2000; $r = 0.76$, Seifert et al., 2004) were already observed. Another good example of a mixed strategy was observed in cluster 4 (the one with lowest number of trials) that was mainly characterized by lower speed conditions (Table 2) but with intermediate absolute speed values (Table 1). Moreover, a great percentage of the cycle was in out-of-phase pattern, expressed by a CRP value, and a very high standard deviation of CRP was reported suggesting an unstable irregular coordination pattern.

The second most used coordination pattern was the one represented by cluster 2, which expressed an intermediate speed and stroke frequency values, and the longest time spent in anti-phase coupling. This coordination pattern seemed to be very consistent as this cluster presented the lower standard deviation of CRP value. All these characteristics seem to suggest that coaches do not often manipulate task constraints in young swimmers training sessions, as a great number of trials were in this cluster and they corresponded to various conditions of speed and stroke frequency. Therefore, the development of functional flexibility might be achieved by training young swimmers to explore various coordination patterns when they swim at different stroke frequencies and swimming speeds (Warren, 2006).

Finally, cluster 6 exhibited a great number of trials swam at 70 and 90% of maximal speed, with various conditions of stroke frequency, except the 110% of preferred stroke frequency. Surprisingly this cluster was also used for fast swim speed conditions (100% of maximal speed) for high stroke frequency conditions (100 to 110% of preferred stroke frequency). Furthermore, when observing CRP values and its standard deviation, as well as the IdC and the relative time spent in each coupling pattern, it showed balanced values comparing to the other clusters, probably because this pattern was not used by the same swimmers for the same conditions. In fact, while some swimmers adopted the cluster 6 for slow speed and low stroke frequency, some other swimmers used it for high speed and high frequency; this pattern well exemplifies inter-individual behavioural variability in the stroke frequency and speed management.

Inter-individual behavioural variability

In the current study, some young swimmers exhibited larger coordination repertoire and switched between several clusters, while some others remained in few clusters. Moreover, some swimmers switched very often, showing inconsistency in their adaptation to task constraints, while some others exhibited more stability according to swimming speeds and/or stroke frequency. These two findings together suggest that inter-individual behavioural variability could be adaptive flexibility as previously hypothesized. In fact, not all variability has shown to be adaptive as our study proposed that the patterns nature and shifting appropriately between them (according to speed and stroke frequency) seems more important than getting high instability (i.e., high number of switching) or/and high range of the repertoire (i.e., high number of patterns). Indeed, a functional adaptation is accepted when an optimal relationship between behaviour and performance outcome occurs. Thus, in the current study, adaptive flexibility would be optimal when upper limb coordination pattern showed consistency between swimming speed and stroke frequency ranges. Movement variability is known to follow the central nervous system development, being observed a U-shape function to characterize the relationship between intra-individual variability in performance and age across lifespan, showing a decrease through childhood and adolescence to adulthood (MacDonald, Nyberg, & Bäckman, 2006). Following this, one hypothesis could be that the motor variability observed in our study might relate to differences stage of development in the central nervous system. However, the swimmers included in the current study are post-pubertal; therefore, the central nervous system have already reached its maturation and we hypothesized that the motor variability could related to sensori-motor system organization. In fact, Deutsch and Newell (2001) showed that motor performance improvement with age further relate to better ability to organize the sensori-motor system to match the task demands rather than reductions in the system noise.

According to the previous description provided for cluster 5, swimmers were considered to functionally adapt their behaviour when using this pattern in the fastest speed and highest stroke frequencies. However, some swimmers (O, K, L and E) have used that cluster in the lowest speed, denoting less appropriate behaviour since it exhibited upper limb coordination pattern further adapted for fast speeds and high stroke frequencies. Likewise, when swimmers used cluster 3 (C, K, L, N, P, E, I, G and H) and 4 (A, I, G and H), they showed a less appropriate behaviour, showing mixed strategies when comparing with other clusters, considering the requested condition and the obtained result (comparison between tables). Finally, cluster 2 and 6 seemed to present ‘intermediate’ states, as swimmers exhibited an intermediate IdC value comparing to other clusters and these clusters were used in contrasted conditions of speed and stroke frequency. These intermediate states can be viewed as inappropriate and non-adaptive, but they can also reflect a transient behaviour used to search new motor solutions and to explore new coordination pattern.

We hypothesized that behavioural fluctuations can be crucial in training process, helping individuals to search for more varied and functional coordination solutions to fit the task dynamics. Davids et al. (2012) stated that there is a limited number of varied but stable performance solutions that can be achieved for a desired outcome.

Indeed, and corroborating with that authors, swimmers Q, R and D that switched among 2, 3 and 4 clusters seemed to show an adaptive flexibility as they were included in cluster 5 in the maximal and sub-maximal speeds and cluster 1 in slow speed (70% speed). Thus, they might use the ‘intermediate’ clusters (2 and 6) in some conditions to explore new possibilities. Hence, these results confirmed our first hypothesis since these swimmers clearly switched between clusters with various coordination patterns, showing a large repertoire of upper limb coordination, but also an adaptive behavioural flexibility.

Moreover, regarding our second hypothesis, it seemed that adaptive behavioural flexibility further related to coordination switching with speed conditions changes than with stroke frequency condition changes. Indeed, we observed high stability of upper limb coordination patterns whatever the stroke frequency conditions of a given speed but more coordination switching between speed conditions. Therefore, manipulating speed conditions could encourage the exploration of different behaviours, notably by designing situation where swimmers can experience supra-maximal swimming speed (such as towing swimmers with an elastic, using swimming flume, or using run and swim situation). Indeed, it would lead swimmers to stabilize functional individual solution (Davids et al., 2012).

What Does This Article Add?

When manipulating swimming speed and stroke frequency, with dominance for speed, different font crawl upper limb coordination patterns could emerge, confirming that these parameters act as the main constraints of the system. However, young swimmers did not change their upper limb coordination, as they remained in catch-up mode, whatever the performed swimming speed and stroke frequency conditions. In one hand, our study highlighted that movement variability might play an important role during training because it can reflect adaptive flexibility to task constraints. In another hand, our findings showed that behaviour variability did not always correspond to functional adaptation but is necessary to explore new possibilities. Thus, the present study suggest that the nature of the patterns, as well as switching appropriately between those patterns (according to speed and stroke frequency), seem more important than getting the highest number of switching or the highest number of patterns (range of the repertoire). These findings show the interest of studying motor variability in ecological context of performance, which goes beyond that swimming context. Finally, the originality of our study was to investigate motor variability both within and between individuals, notably by studying the effect of age (not by comparing young to adult swimmers, but by examining the individual repertoire of young swimmers).

Chapter 4.

Control parameter determination when manipulating task constraints

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Published on Current Research in Motor Control V (2016), pp. 246-251.

Introduction

The emergence of dynamical system approach has stimulated a radical reassessment of the movement variability concept (Glazier, Wheat, Pease, Bartlett 2006). Based on the central issue highlighted by Bernstein (1967), the main concern has been to understand how systems with many degrees of freedom cooperate with each other to produce regularly and orderly behaviours at a macroscopic level (Kelso,Tuller 1984). The very first study that attempted to understand how these mechanisms are guided and controlled focused on the analysis of a simple movement of two fingers (Kelso 1984). In this study and other related studies (e.g. Kelso, Jeka 1992; Schmidt, Shaw, Turvey 1993), a transition from a syncopation to synchronization was observed when the stimulus frequency exceeded a critical value. Those experiments showed that, with increasing movement frequency, an abrupt in-phase symmetrical mode appears (a simultaneous activation of homologous muscles). Hence, it was observed that two equally stable coordination modes can be attained – the in-phase and anti-phase – depending on movement frequency (Fuchs, Kelso 2009). This finding was shown not to be restricted to finger movements.

In addition, another interesting related issue consists that these changes in behaviour occurs in a sudden and completely involuntary way, suggesting that these alterations in coordination might be ordered by modifications in a single parameter (Haken, Kelso, Bunz 1985). The so-called control parameter, firstly described by Haken (1977), which could have an internal or external origin that when manipulated, controls the system in a non-specific way and is capable to move the system through its repertoire of patterns, causing them to change. To identify a control parameter, it is necessary to observe if its variation causes qualitatively or discontinuously changes in the system’s behaviour (Kelso 2009). When the control parameter reaches a critical value, instability occurs, leading to the formation of new (or different) pattern. Therefore, fluctuations or movement variability are not just noise, rather they allow the system to discover new and more adaptive behavioural patterns (Kelso 2001).

Specifically in swimming, namely front crawl technique, velocity and stroke frequency are considered the most influencing parameters on the inter-arm coordination (e.g. Chollet, Chalies, Chatard 2000; Potdevin, Bril, Sidney, Pelayo 2006). In those studies, the index of coordination (IdC, an indicator providing the temporal gap between two propulsive actions), found a high positive correlation between IdC and velocity as well as stroke frequency. However, as the velocity results from the product between stroke length and stroke frequency, it could be expected that any increase of the swim velocity would lead to an increase of stroke frequency, which is mainly accompanied by an increase of IdC (being this latter positively correlated with velocity) the doubt if stroke frequency or velocity is the real control parameter, or even if it is the combination of both parameters still remains. Therefore, the aim of this study was to could control the inter-arm coordination mode in front crawl swimming.

Methods

Eighteen young swimmers (5 boys and 13 girls) participated in this study. Their main characteristics were: 13.9 ± 0.9 years old, 166.5 ± 8.1m of height, 169.5 ± 8.0 of arm span, 59.5 ± 8.1 kg of body mass and 8.2 ± 2.8 years of practice. Each swimmer performed a 15 x 50m front crawl protocol of five repetitions at 100, 90 and 70% of their maximal velocity and, within each condition, at 90, 95, 100, 105 and 110% of swimmers' preferred stroke frequency. A written informative consent was signed by parents, with all the information regarding tests carried out, being all the procedures previously approved by the local ethics committee and performed according to the Declaration of Helsinki.

The target stroke frequency was controlled by an underwater metronome, placed inside the swim cap (Tempo Trainer Pro, Finis®). Seven surface and six underwater cameras (Qualisys AB, Gothenburg, Sweden) were used to assess the inter-arm coordination through the continuous relative phase (CRP) and the IdC. The assessment of CRP between the two arms (arm-shoulder-trunk angle) was performed for one single cycle (distance travelled between two consecutive entries of the same hand), recorded in the central part of the pool to avoid the start and turn effects. To compare cycles of different time duration each cycle was expressed in percentage. The CRP was assessed through the subtraction of the phase angle of one oscillator from the other at each point in time over the entire stride (i.e. the left shoulder phase angles was subtracted from the right one). Following Seifert, Delignieres, Boulesteix, Chollet (2007) the three different modes corresponds to: (i) in-phase, when it is observed a synchronization between the arm actions, therefore CRP occur between 330º < CRP < 30º; anti-phase, correspond to an opposite action, thus CRP is considered when 150º < CRP < 210º; and out-of-phase, when there is a lag time between the two actions, degrees between 30º < CRP < 150º and 210º < CRP < 330º. Conversely, IdC provided information about the relative time between two propulsive actions by measuring the time between the beginning of propulsion of the first right arm cycle and the end of propulsion of the first left arm cycle, and between the beginning of propulsion of the second left arm cycle and the end of propulsion of the first right arm cycle (Chollet, Chalies, Chatard 2000).

Data were tested for normality of distribution was checked with the Shapiro-Wilk test. Mean and SD were calculated for all measured parameters. To compare velocity and stroke frequency a two-way repeated measures ANOVA was applied (3 velocities x 5 stroke frequencies). The statistical significance was set at $p < 0.05$.

Results

It was observed that in all studied parameters statistical differences were noticed between velocities, with the velocity of 90% registering the higher values of CRP (210.03 ± 2.43), with a greater time spent in in-phase mode (3.29 ± 0.37) and with the higher IdC value (-12.74 ± 0.74; -8.18 ± 0.74 and -9.30 ± 0.74 for velocity 100% and 70%, respectively). Regarding the effect of stroke frequency alone, only time spent in anti-phase ($F_{(4, 204)} = 5.83$, $P<0.01$) and out-of-phase ($F_{(4, 204)} = 6.40$, $P<0.01$) presented differences. Nevertheless, no linear changes were observed with increasing stroke frequency, but a higher time spent in anti-phase was observed in the frequency of 110% (90%: 49.94 ± 2.15; 95%: 53.29 ± 1.76; 100%: 47.25 ± 1.79: 105%: 47.12 ± 1.62; 110%: 55.23 ± 1.65) and a pronounced time spent in out-of-phase was noticed in the frequency of 100% (90%: 48.02 ± 2.16; 95%: 44.82 ± 1.72; 100%: 50.92 ± 1.78: 105%: 50.38 ± 1.53; 110%: 42.92 ± 1.66). Similarly, it was observed differences in these two parameters when analysing the interaction between velocity and stroke frequency was observed, and likewise, any pattern of changes was identified.

Discussion

The aim of this study was to analyse if velocity and stroke frequency could control the inter-arm coordination pattern in front crawl swimming. In fact, the present study support the link already shown in some studies, where a positive correlation with these parameters and inter-arm coordination was noticed (e.g. Chollet, Chalies, Chatard 2000; Potdevin, Bril, Sidney, Pelayo 2006). However, velocity exerted a greater influence in behaviour comparing to stroke frequency, at least within the ranges used in this study.

Considering that velocity has a direct dependence on stroke frequency, it was expected that the combination of both would influence behaviour. However, when studying coordination on swimming, some characteristics should be considered, as they could influence the behaviour adopted. For instance, it is well known that water is 800 times denser than air (Toussaint, Carol, Kranenborg, Truijens 2006) and that drag increases with increasing velocity. Thus, to maintain an optimum effectiveness under these changeable environmental constraints, swimmers need ability to quickly adjust their swimming techniques and the patterns of propulsive forces produced within the task constraints imposed by the rules governing the specific swimming cycle (Toussaint, Carol, Kranenborg, Truijens 2006). This could suggest that young swimmers are accustomed to swim at the highest and the lowest velocities as they seemed to have more difficulties to adapt in the velocity of 90% as they showed frequently an out-of phase mode and a great lag time between propulsive phases (more negative IdC).

Another aspect that should be considered is related to the body roll movement, which invariably decreases with the increasing stroke frequency, causing decreases in the arm lateral movements and the hand path becomes more linear during the pull phase (Hay, Liu, Andrews 1993). In these conditions the swimmer's hand could accomplish a slippage through the water (Seifert, Toussaint, Alberty, Schnitzler, Chollet 2010), leading to an increase of stroke frequency. Nonetheless, as the movement of hand path is inappropriate, it is not accompanied by velocity, thus IdC values could increase but their propulsive phases are not efficient. This could explain why the relationship between IdC and stroke frequency are not always visible and in a progressive way (increasing IdC with concomitant increase in stroke frequency).
In summary, to enlarge the repertoire of front crawl swimming coordination, it seems that swimmers should focus more in the manipulation of velocity rather than stroke frequency. However, it might be considered that these swimmers could be in the middle of their learning process, which could suggest that the requested increases of stroke frequency led swimmers to perform a wrong hand path.

Chapter 5.

A multi-analysis of performance in 13-15 year-old swimmers: a pilot study

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Published on Book of proceedings of the XII International Symposium on Biomechanics and Medicine in Swimming. pp 242-248. Canberra, Australia.

Introduction

Swimming performance is a multi-factorial phenomenon depending on several factors such as energetics, biomechanics, hydrodynamics, anthropometrics and strength parameters (Poujade et al., 2002; Barbosa et al., 2009). Considering that heavy training loads start at relatively young ages, it seems important to assess which parameters best predict swimming performance.

In a longitudinal study, Tella et al. (2002) reported that the improvement observed in young swimmers performance results from an increase in stroke length (SL), which reflects, in part, the increase of anthropometrical characteristics (arm span, height and hands and feet length). Similarly, Chatard et al. (1990) stated that performance is related to passive drag, which depends on anthropometric factors. More recently, in a swimming performance's multivariate analysis, it was found that higher height and arm span, characterized the best male swimmers (Saavedra et al., 2010). Other studies found similar results (e.g. Lätt et al., 2010; Geladas et al., 2005), allowing researchers to conclude that usually higher height and arm span benefits swimming efficiency (i.e. higher SL) (Saavedra et a., 2010) and a better glide (Geladas et al., 2005; Toussaint and Hollander, 1994). However, this larger SL could be also related to a hyperflexibility presented by swimmers, which benefit the glide and create less resistance (they could streamline their body to a greater extent). This contributes to a more laminar and less turbulent flow around the pressure points, such as the shoulder, hip, knee, ankle, where most of the changes in body shape occur (Chatard et al., 1990).

Many sports depend mainly upon muscular strength and aerobic enhancement especially at a competitive level (Leverittet al., 2000), as in swimming. In fact, studies showed positive effect of dry-land upper limb strength training, varying the gains in sprint performance between 1.3 and 4.4% (Strass, 1988; Costill, 1999). Regarding young swimmers, it was noticed that the significant increase in velocity between 12 to 14 years old is coincided with a significant increase in the mean force production

(Taylor et al., 2003). Moreover, strength training could allow the enhancement in coordinative profile, helping the swimmer to improve his/her technique (Maglischo, 2003). In fact, when competitive young swimmers are involved in strength training, to take full benefit of an increase in muscle strength, coordination needs to be adapted (Newton et al., 2002). The swimmer has to modify the control of the neuromuscular system, commonly referred as coordination, timing or technique, to actually produce an increased in-water performance (Faigenbaum, 2000). Unfortunately, results that try to support this idea remain inconclusive (Girold et al., 2007; Aspenes et al., 2009). Nevertheless, it was found positive associations between in-water and dry-land tests (Morouço et al., 2011a), as well as strong relationship between mean absolute force and the time at 50 m for the four swimming techniques (Morouço et al., 2011b).

The aim of this study was to determine which parameters are predominant to achieve better performances in age group swimmers. It was hypothesized that faster swimmers are taller and achieve higher values of mean (F_{mean}) and maximal force (F_{max}). Moreover, it was hypothesized that faster swimmers present a more continuous arm coordination movement pattern, reflected through higher index of coordination (IdC) values.

Methods

Participants

Eighteen young female swimmers were divided in two groups considering their performance level. The local Ethics Committee approved the experimental procedures, and the swimmer’s parents signed a consent form in which the protocol was described. Their main characteristics and swimming performance level, assessed as best scores in the FINA table, are presented in Table 1.

Table 1. Main characteristics of the two groups of swimmers.

	Age	Years of Practice	Ranking*	Weight	Height	Arm Span	Foot length	Hand length
Group 1	14.00 (0.76)	10.25 (2.43)	592.50 (85.08)	53.95 (7.96)	160.63 (5.09)	162.50 (4.81)	22.83 (1,28)	16.95 (0.46)
Group 2	13.40 (0.52)	8.20 (1.81)	516.70 (53.11)	49.25 (5.83)	161.10 (8.05)	159.62 (9.70)	22.20 (0.98)	17.40 (1.43)

*Statistically significant differences between groups ($P < 0.05$).

Experimental procedures

The tests were performed in a 25 m indoor pool. A warm-up of low to moderate swimming intensity was conducted. Each swimmer performed four different tasks: (i) an anthropometrical and flexibility evaluations; (ii) 25 m front crawl at 50 m race pace; (iii) 30 s tethered swimming maximal effort and (iv) ten incremental velocity bouts on the MAD-system. For the kinematic evaluation, swimmers were videotaped in the sagittal and frontal plane using two underwater video cameras (Sony® DCR-HC42E, 1/250 digital shutter, Nagoya, Japan), placed inside a sealed housing (SPK – HCB waterproof box, Tokyo, Japan), recorded two complete underwater upper limb cycles. A bi-dimensional image calibration structure (6.30m^2, and 13 calibration points) was used to transform the virtual coordinates into the real ones. Kinematical analysis was performed using APASystem software (Ariel Dynamics, San Diego, USA), digitizing manually and frame by frame (at 50 Hz) the anatomical landmarks corresponding to the skin markers. The hip (femoral condyle) and, on both sides of the body, the distal end of the middle finger, the wrist, the elbow, the shoulder and the ankle were digitized.

Anthropometric and flexibility measurement

The anthropometric measurements were taken according to standardized procedures (Saavedra et al., 2010), including body dimensions as height and arm span, foot and hand length. Regarding flexibility, the shoulder joint maximal flexion and extension was analyzed, using a goniometer.

Biomechanical parameters

To perform the 25 m front crawl at 50 m race pace, swimmers started in the water and swam alone, without the pressure of opponents, to reduce the drafting or pacing effects (Barbosa et al., 2010). Afterwards, swimmers were informed of their performance time, which was expected to be within ± 2.5 % of the targeted race speed; when the time was unexpected, the subject repeated the trial after a 30 min interval.

Swimming velocity was assessed through the ratio of the displacement of the hip in a stroke cycle to its total duration. SL was determined by the horizontal distance travelled by the hip during a stroke cycle, and stroke rate (SR) as the number of stroke cycles performed per min. The stroke index (SI) was computed by the product of velocity and SL. The SL ration was also calculated. The IdC was also measured through the images recorded, by measuring the time between the beginning of propulsion of the first right arm stroke and the end of propulsion of the first left arm stroke, and between the beginning of propulsion of the second left arm stroke and the end of propulsion of the first right arm stroke (Chollet et al., 2000). IdC was calculated based on the division of the arm actions in four phases: (i) entry/catch, corresponding to the time since the entry of the hand in the water until it starts to make the backward movement; (ii) pull, from the end of the previous action until achieving vertical alignment of the shoulder (first propulsive phase); (iii) push, from the end of the previous action to the exit the hand of the water (second propulsive phase) and (iv) recovery, which is the time from the exit of the hand until its new entry. The IdC and each stroke phase were expressed as the percentage of the duration of a complete arm stroke; the sum of the pull and the push phases, and of the catch and the recovery phases, indicate the duration of the propulsive and non-propulsive phases, respectively.

Tethered swimming

Each swimmer performed 30 s front crawl at maximal intensity in tethered swimming. The subjects wore a belt attached to a steel cable with 5 m length (sufficiently stiff that its elasticity could be neglected), which was connected to a load-cell. The force signal was acquired by an A/D converter (BIOPAC System, Inc., Goleta, CA, USA) at a sample rate of 500Hz and filtered with a low pass digital filter with a cut-off frequency of 10Hz. Preceding the starting signal, swimmers adopted a horizontal position with the cable fully extended, starting the data collection only after the first stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually observed immediately before or during the first arm action (Morouço et al., 2011b). The test ending was set through an acoustic signal. Swimmers were told to choose the breathing patterns that normally apply in the 50 m front crawl event. The graphic force/time was registered and analyzed to obtain the values of F_{mean} (mean value of force within 30 s) F_{max} (value obtained in the first 5 s), minimum force (F_{min} - mean value over the last 5 s). Through these values the fatigue index (FI) was calculated: fatigue index = [(Fmax - Fmin) / Fmax] * 100 (Rohrs & Stager, 1991; Morouço et al., 2012).

MAD-System

To measure drag at maximal velocity, swimmers performed ten incremental velocity bouts in MAD-system. This apparatus require the swimmer to push-off sixteen fixed pads attached to a 23 m rod, which was fixed 0.8 m below water surface, and had a standard distance of 1.35 m between each pad (Toussaint et al., 2004; Ribeiro et al., 2013). The rod was instrumented with a force transducer allowing measurement of push-off force from each pad. The force signal was acquired by an A/D converter (BIOPAC System, Inc., Goleta, CA, USA) at a sample rate of 500Hz and filtered with a low pass digital filter with a cut-off frequency of 10Hz. Assuming a constant swimming velocity, the mean force equals to mean drag force and, hence, the 10 velocity/force ratio data were least square fitted according to Equation 1:

$$D = A \cdot v^n \ (1)$$

where D is active drag force, A and n are parameters of the power function and v represents the swimming velocity. For each subject A and n were estimated using Equation 1 (Matlab version R2012a, Mathworks, Inc., Natick, MA, USA) with Levenberg-Marquardt algorithm (Toussaint et al., 2004). Swimmers only used their arms, their legs were supported and fixed by a pullbuoy. The first and the last push off are not included in the analysis in order to eliminate the influence of the push off from the wall and the deceleration of the swimmer at the end of the length.

Statistics

Data were tested for normality of distribution and the statistical analysis performed was based on exploratory data analysis. Mean and *SD* were calculated for all measured parameters. One-way ANOVA was performed to compare groups ($p < 0.05$). The effect size of each variable was also calculated.

Results

The mean and SD values regarding anthropometric, flexibility of shoulder joint, biomechanical, strength and active drag parameters are described in Table 2.

Table 2. Mean (SD) values, p-values and effect size regarding anthropometric, flexibility, biomechanical, strength and drag variables between group 1 (G1) and group 2 (G2).

Parameters	G1 (n = 8)	G2 (n = 10)	p-value	Effect size
Anthropometric				
Height (cm)	160.6 (5.1)	161.1 (8.1)	0.89	0.13
Arm span (cm)	162.50 (4.81)	159.62 (9.70)	0.46	3.53
Foot length (cm)	22.83 (1,28)	22.20 (0.98)	0.26	7.94
Hand length (cm)	16.95 (0.46)	17.40 (1.43)	0.41	4.34
Flexibility				
Maximal right shoulder flexion (º)	195.00 (6.55)	187.40 (3.50)	0.006	38.48
Maximal left shoulder flexion (º)	191.25 (2.31)	183.00 (4.22)	<0.001	60.50
Maximal right shoulder extension (º)	67.50 (4.63)	68.00 (10.33)	0.90	0.10
Maximal left shoulder extension (º)	75.00 (5,35)	69.00 (8,43)	0.10	19.05
Biomechanical				
velocity (m/s)	1.68 (0.02)	1.58 (0.04)	<0.001	73.33
SL (m)	1.99 (0.15)	1.83 (0.18)	0.06	20.46
SR (cycles/min)	50.89 (3.81)	52.19 (4.17)	0.51	2.82
SI ($m^2.s^{-1}$)	3.34 (0.23)	2.89 (0.36)	0.007	37.56
IdC (%)	-8.60 (1.44)	-5.53 (3.15)	0.02	28.76
Strength				
Mean Force (N)	169.6±75.4	119.0±14.4	0.05	21.48
Maximal Force (N)	178.7±73.5	127.0±14.6	0.04	22.99
Fatigue Index (N)	11.42 (5.08)	11.99 (5.55)	0.98	0.003
MAD-System				
Drag at maximal velocity (N)	59.00 (20.60)	50.70 (11.50)	0.29	6.92

No differences were found in anthropometric characteristics, active drag and FI between groups. G1 showed higher shoulder flexion, SL, SI, F_{mean} and F_{max} than G2. Although both groups presented catch-up coordination mode, IdC was lower in G1. Regarding effect size, it is possible to observe that swimming velocity is the main parameter that distinguishes the two groups. However, the ability to obtain a wide range of left shoulder flexion, seems to play an important role. Probably associated with these two last parameters, appears the maximal right shoulder flexion and SI. Conversely, FI, maximal right shoulder extension and height were the parameters less important to distinguish these two groups of swimmers.

Discussion

The aim of this study was to determine which parameters are predominant to achieve better performances in age group swimmers. The higher SL, SI, F_{mean}, F_{max}, shoulder flexion, better hydrodynamic profile, but lower IdC values, were the most important parameters. As both groups have similar anthropometrical characteristics, the higher velocity attained by G1 can be explained by a better technique (particularly the higher SL and SI values). Moreover, strength characteristics also seem to play an important role, since faster swimmers achieved higher values of F_{mean} and F_{max}, as hypothesized. The second hypothesis was not confirmed, as faster swimmers presented a more negative IdC than slower swimmers, i.e. they presented a higher lag time between propulsive arm phases. However, both groups adopted catch-up coordination mode.

The better swimming technique showed by G1 was confirmed through a higher SL values presented by this group, as both G1 and G2 presented similar anthropometric values. Moreover, G1 also achieved higher SI values, which is explained by its dependence of velocity and SL. In fact, SI is an index that represents swimming technical efficiency, since higher values denote that the swimmer covers a given distance with fastest time and with less number of strokes. Regarding young swimmers, Lätt et al. (2010) have already reported the importance of biomechanical parameters, showing that these parameters may explain 90.3% of the variance in 100-m swimming performance. Moreover, these results could be influenced by flexibility, since G1 showed greater range of shoulder flexion, which could be expressed in the higher SL values observed in this group. Thus, with a streamlined body, these swimmers could express a better glide, creating less resistance, and consequently, a better hydrodynamic profile. The catch-up mode adopted by young swimmers was in opposition to what was hypothesized, faster swimmers showed lower IdC values, representing a less continuous arm coordination movement pattern. This result contrast to those obtained by adult elite swimmers (e.g. Chollet et al., 2000, Seifert et al., 2007) and with a study conducted on two groups (pubertal and post-pubertal) of young swimmers that presented different velocities (Silva et al., 2012). The reason for these results could be related to the higher strength values applied by G1 during the propulsive arm phases, i.e. as G1 presented higher strength values (F_{mean} of 169.6±75.4 vs. 119.0±14.4 and F_{max} of 178.7±73.5 vs. 127.0±14.6 for G1 and G2, respectively), their movement could be faster and more effective. Indeed, Sozañski (1999) stated that the age between 11 to 14 years old are characterized as a period of versatility, for mastering the technique and to prepare for a progressive workout.

An optimal level of strength and power is necessary for successful performance in many sports, and swimming is no exception (Newton et al., 2002). Indeed, faster swimmers presented higher values of F_{max} and also F_{mean}, suggesting that force is very important for maximal efforts. In addition, FI was similar for both groups supporting the hypothesis that propulsive forces were more efficiently applied by G1. In fact, it was reported that strength training improves swimming performance (Toussaint et al., 1990; Girold et al. 2007), which result in an increase in SL (Toussaint et al., 1990), a reduction in SR (Girold et al. 2007) and in an increase in tethered swimming force (Toussaint et al., 1990; Girold et al. 2007). These results could also influenced drag, as in a longitudinal study (2.5 year period of growth) with young swimmers, Toussaint et al. (1990) showed that, with no differences in drag values, the 14% improvement of the swimming performance in the 100 m time performance were related to a higher maximal force (34%), velocity (12%), and power (49%) measured on the MAD-system. Indeed, in the present study, even though G1 attained higher velocity, similar drag values were presented by the groups, which suggests a better hydrodynamic profile of G1.

As a conclusion, higher performances in young female swimmers, are linked to a greater SL, SI, F_{mean}, F_{max}, shoulder flexion, better hydrodynamic profile, but also to lower IdC values.

Chapter 6.

Integrated analysis in young swimmers sprint performance

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Submitted for publication on European Journal of Sports Science.

Abstract

This study aimed to analyse young swimmers performance considering their sex and skill level. Forty nine swimmers (23 boys and 26 girls: 15.7 ± 0.8 and 14.5 ± 0.8 years, respectively) were assessed for anthropometry, flexibility, strength, active drag, coordination and general biomechanical parameters in a 50-m maximal front crawl bout. Thirteen Qualisys cameras (seven aerial and six underwater) assessed kinematics. A MANOVA was used to detect different patterns regarding skill level and sex, and a multiple linear regression predicted performance (speed) for each sex. Significant differences where noticed between skill levels in swimming speed, stroke frequency, stroke index and intra-cyclic velocity variations (all $p < 0.05$), but the major differences were noticed when comparing sexes (anthropometrics, shoulder flexibility, speed, stroke frequency, stroke length, active drag, mechanical power, power per stroke, maximal and mean force ($p < 0.05$). Considering the included variables, only male performance could be predicted ($F_{(13, 22)} = 21.69$, $p < 0.01$, $R^2 = .97$, adjusted $R^2 = .92$), with stroke index, left shoulder flexion and index of coordination showing an important role to achieve better performances. Data evidenced that age-group swimmers are still actively involved in the learning process, with the organismic constraint as sex (and all the inherent features) with a stronger influence on performance. Therefore, during training sessions different feedbacks should be given according to swimmers sex.

Keywords: motor organization, expertise, young swimmers, performance, gender differences.

Introduction

Talent identification has been a central concern for researchers and sport analysts, with expertise traditionally associated with the capacity to replicate a specific coordination pattern consistently through movement automaticity increases (Ericsson, Krampe, & Tesch-Römer, 1993). However, that concept neglected the range of interacting constraints on each individual (Davids, Button, & Bennett, 2008), characterizing a skilled movement as a rigidly stable motor solution. In fact, between individuals variability have been reported (e.g. Srinivasan, Rudolfsson, & Mathiassen, 2015; van Dieën, Oude Vrielink, & Toussaint, 1993), leading to assume that a single movement goal can be reached through several different ways (Starkes & Allard, 1993). Nevertheless, some factors have been shown to be associated with movement variability as: (i) skill level, changing from less to a greater variability during the skill acquisition (Hong & Newell, 2006); (ii) sex, with males showing greater variability (Svendsen & Madeleine, 2010); (iii) age, showing a decrease through childhood and adolescence to adulthood (MacDonald, Nyberg, & Bäckman, 2006); and (iv) chronic pain, that increases variability (Madeleine, Mathiassen, & Arendt-Nielsen, 2008).

Follow that dynamical movement perspective, each individual are considered to be unique and shaped by many factors including experience, learning, development, morphology and genes, which interact to define performance and the expertise acquisition in sports (Davids et al., 2008). Those factors were summarized by Newell (1986) in three categories: (i) organismic, considering the individual anatomical and physiological characteristics; (ii) environmental that are external to the organism and are not manipulated by the experimenter, and (iii) task, referring to the goal, being divided in three types: the task goal, its rules or instructions, and the tools or devices used. Therefore, studies in expertise topic have advised a multidisciplinary approach, to identify the range of interacting constraints imposed on individuals' performance (Phillips, Davids, Renshaw, & Portus, 2012).

In swimming, some studies have been done including several characteristics and variables searching for the most important one(s) to achieve better performances, existing no consensus regarding young swimmers. In fact, some authors highlighted anthropometrics (e.g. Douda, Toubekis, Georgiou, Gourgoulis, & Tokmakidis, 2010; Jurimae et al., 2007), biomechanics – stroke index (SI), stroke length (SL), stroke frequency (SF) and intra-cyclic velocity variations (e.g. Figueiredo, Silva, Sampaio, Vilas-Boas, & Fernandes, 2015; Latt et al., 2009), hydrodynamics (e.g. Morais et al., 2016; Silva et al., 2014), propelling efficiency (Barbosa et al., 2010; Morais et al., 2016) –, strength (e.g. Douda et al., 2010; Morais et al., 2016), coordination (Silva et al., 2014) and physiologic – as VO_{2peak} (e.g. Jurimae et al., 2007; Latt et al., 2009), anaerobic power (Vitor & Bohme, 2010) and energy cost (Latt et al., 2010).

Regarding those young swimmers studies, it was observed that a great part included only boys, and those that included both sexes, were conducted in swimmers with ~12 years of age (in pre- or pubertal stage), with the maturation process having an important impact on performance. Considering the following swim stage (ages from 14 to 16), including swimmers with a complete maturational process or closer to the end, only males were analysed (e.g. Latt et al., 2010; Nasirzade et al., 2015) and in mid- or long-distance races (100, 400 and 200-m, respectively). Moreover, in these ages, few studies included coordinative variables, with the two studies found using a temporal method, the most widely used in swimming. Therefore, this study aimed to conduct a multi-varied analysis of young swimmers performance to determine which parameters are predominant to achieve better performances, when analyzing the effect of sex and skill.

Methods

Twenty-three male and twenty-six female swimmers (15.7 ± 0.8 and 14.5 ± 0.8 years old, respectively) participated in this study, all situated in post pubertal maturational stage (stage 4 or higher; Tanner & Whitehouse, 1982). Swimmers were divided in two distinct skill level groups with speed below or above 30s for more and less skilled swimmers, respectively. That evaluation was conducted by swimmers and, afterwards discussed with their coach and other adult team member. Firstly, anthropometrical (height, arm span and body mass) and flexibility evaluations (shoulder joint maximal flexion and extension) were conducted according to standardized procedures (Norkin & White, 2009; Saavedra, Escalante, & Rodriguez, 2010). In a 25-m indoor pool, after a 1000-m warm-up at low to moderate swimming intensity, each swimmer performed three different evaluations in front crawl: (i) 50-m at maximal speed with in-water starts to measure performance; (ii) 30-s tethered swimming maximal effort to measure strength and fatigue; and (iii) 25-m maximal speed on measuring active drag system (MAD-system) to asses active drag at maximal speed. The local ethics committee approved the procedures and all the swimmers parents signed a consent form which the protocol was explained.

While performing the 50-m maximal test, swimmers used ten anatomical reflective landmarks in each body side (iliac crest, acromion, lateral humerus epicondyle, radius- and ulnar-styloid processes) enabling the creation of 3D dual media volume, where the orthogonal axes were defined as x, y and z for horizontal, medio-lateral and vertical (z = 0 defines water surface) movements, respectively. A thirteen-camera setup (MoCap) was used, with seven dry-land plus six underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 100 Hz. The calibrated volume was defined using underwater, above water and twin system to merge the first and the latter calibrations (according to the manufacturer's guidelines).

Performance was determined by swimming speed that was computed as the ratio of the hip displacement (SL in $m \cdot cycle^{-1}$) in an upper-limb cycle (distance travelled between two consecutive entries of the same hand) to its total duration. Stroke frequency (SF in $cycles \cdot min^{-1}$) was determined as the number of upper-limb cycles performed per minute. Stroke index (SI in $m^2 \cdot s^{-1} \cdot cycle^{-1}$) was computed by the product of speed and SL. Intra-cyclic velocity variations (IVV) were calculated through the ratio between speed standard deviation to the mean hip speed. To measure coordination two methods were used: (i) a temporal method, index of coordination (IdC), assessed following Chollet, Chalies, and Chatard (2000), whom indicated that exists three different coordination modes: catch-up (IdC < 0), opposition (IdC = 0) and super-position (IdC > 0); (ii) a spatio-temporal method, continuous relative phase (CRP) that was calculated through the subtraction of the phase angle of the two oscillators at each point in time over the entire cycle (i.e. the left shoulder phase angles was subtracted from the right one), with three modes varying from 0 to 360º: in-phase (0º ± 30º), anti-phase (180º ± 30º) and out-of-phase (30º < CRP < 150º and 210º < CRP < 330º).

Each swimmer performed 30-s tethered front crawl test, with normal breathing, at maximal intensity using a belt attached to a 5-m length steel cable (sufficiently stiff that its elasticity could be neglected) connected to a load-cell. With the cable fully extended, the test start and end were defined through an acoustic signal, with data collection starting when the first upper-limb cycle was completed to avoid the cable extension inertial effect usually observed immediately before or during the first upper-limb action. Force signal was acquired by an A/D converter (BIOPAC System, Inc., Goleta, CA, USA) at a sample rate of 500 Hz and filtered with a low pass digital filter with a cut-off frequency of 10 Hz. The mean, maximal and minimum forces (using 30s, the first 10s and the last 5s for F_{mean}, F_{max} and F_{min}, respectively) and fatigue index (FI = [(Fmax - Fmin) / Fmax] * 100; Morouço, Vilas-Boas, & Fernandes, 2012) were calculated.

To assess hydrodynamic drag, swimmers performed 25-m front crawl at maximal speed on MAD-system using only upper-limbs as described by Ribeiro et al. (2016). Assuming a constant swimming speed, the mean force equals to mean drag force and the ten speed/force ratio data were least square fitted according to $D = A \cdot v^n$, where D is active drag force, A and n are parameters of the power function and v represents swimming speed (Toussaint, Roos, & Kolmogorov, 2004). Mechanical power output ($P_o = D \cdot v$), work per stroke ($D \cdot SL$) and propelling efficiency ($e_p = A \cdot v^3_{free} / A \cdot v^3_{MAD}$) were also assessed.

Mean and standard deviations were calculated for all variables and normality and homoscedasticity assumptions were checked with Shapiro-Wilk and Levene tests, respectively (SPSS Statistics version 24.0). A two-way MANOVA was conducted to analyse the sex and skill level and their interaction effects in all included variables. Afterwards, a multiple linear regression (MLR) for each sex, computed with the enter method, to explain performance (speed) using the following parameters: arm span, right and left shoulder flexion and extension, SI (SF and SL were not included in the model since its product results in speed), IVV, CRP, SD of CRP, IdC, P_o, e_p and F_{max}. Also the relationship between performance (speed) and all the parameters included in this study through the Pearson correlations was accomplished.

Results

Figures 1 to 4 displayed the behaviour of all studied variables. Statistical differences were detected between sex ($F_{(3, 45)} = 10.17$, $p < 0.01$, $\eta^2 = 0.92$) and skill level ($F_{(3, 45)} = 6.72$, $p < 0.01$, $\eta^2 = 0.89$), but no significant interaction effect (sex x skill level) was observed ($F_{(3, 45)} = 1.40$, $p = 0.22$, $\eta^2 = 0.62$).

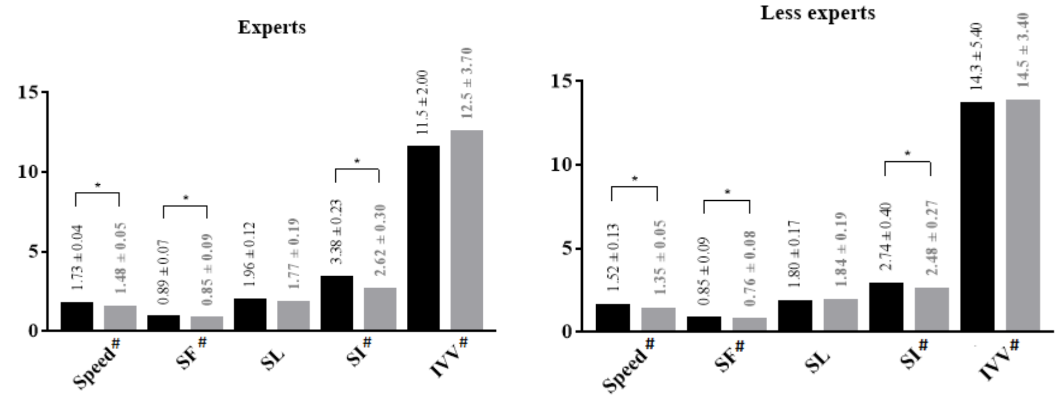

Figure 1. Males (black bar) and females (grey bar) differences for expert and less expert swimmers in biomechanical variables – speed, stroke frequency (SF), stroke length (SL), stroke index (SI) and intra-cyclic velocity variation (IVV). The * and # means gender and skill level differences, respectively.

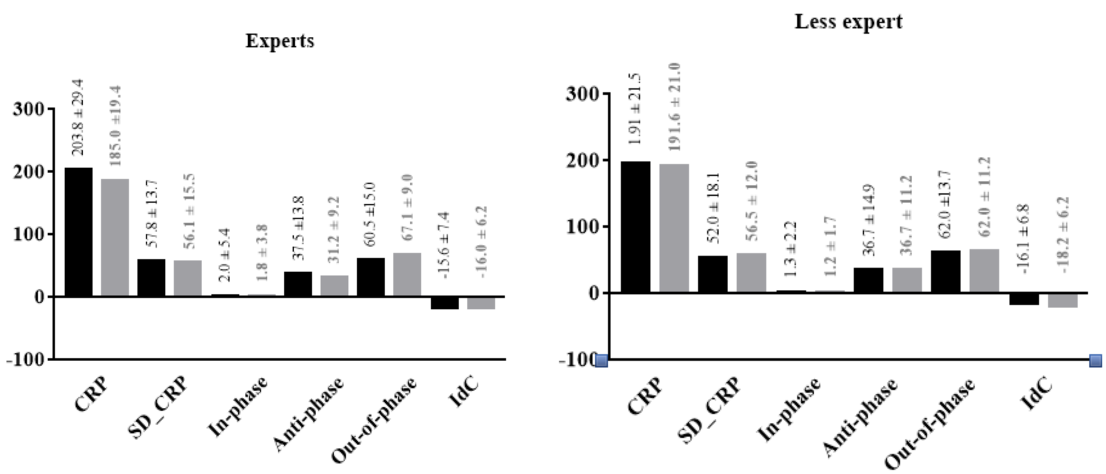

Figure 2. Males (black bar) and females (grey bar) differences for expert and less expert swimmers in coordinative variables – continuous relative phase (CRP), standard deviation of continuous relative phase (SD_CRP), in-phase, anti-phase, out-of-phase and index of coordination (IdC).

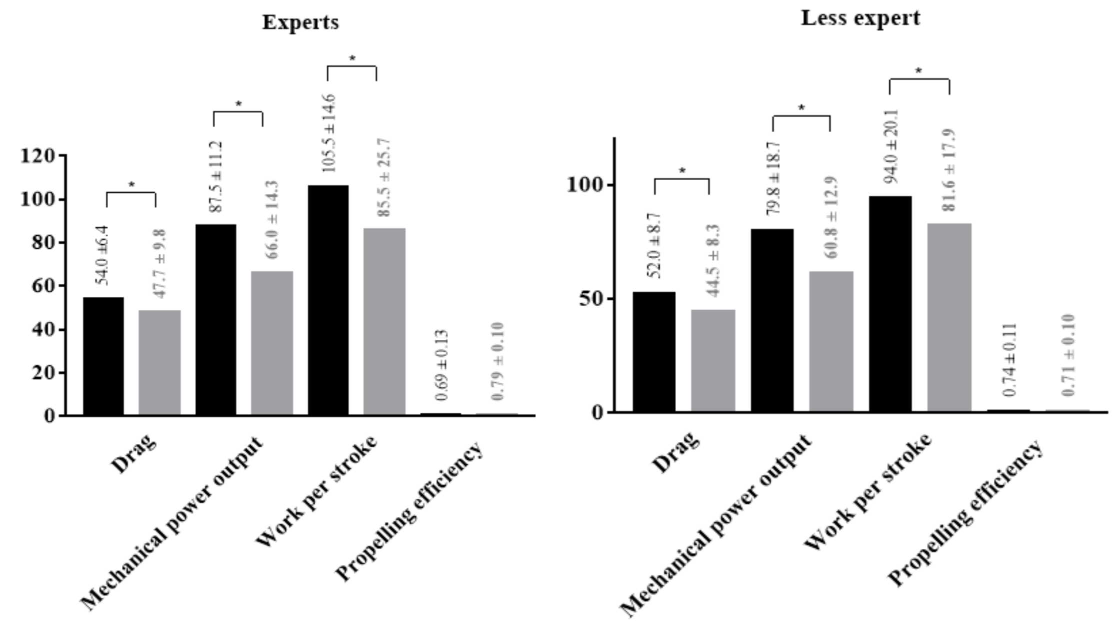

Figure 3. Males (black bar) and females (grey bar) differences for expert and less expert swimmers in hydrodynamic variables. The * means gender diferences.

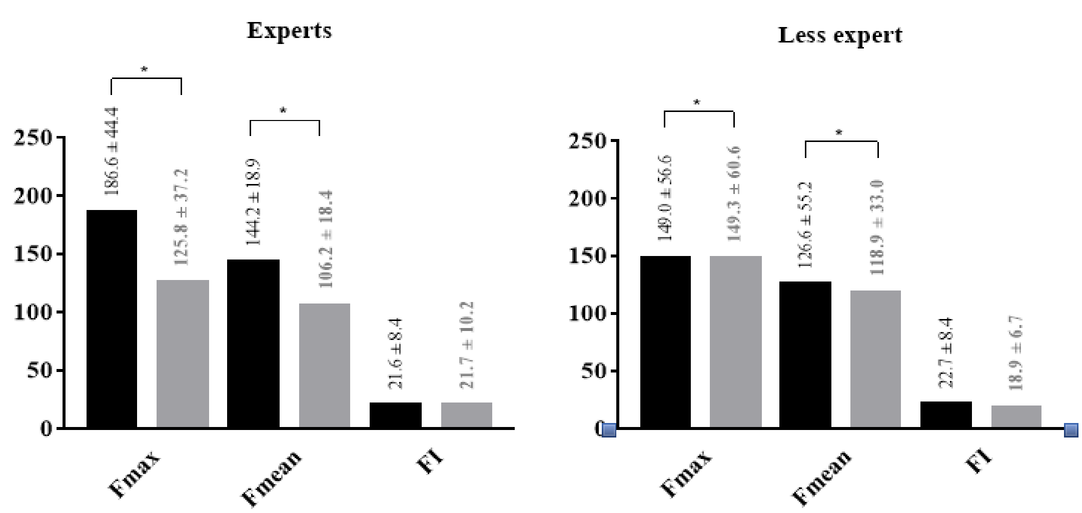

Figure 4. Males (black bar) and females (grey bar) differences for expert and less expert swimmers in strength variables – maximal force (F_{max}), mean force (F_{mean}) and fatigue index (FI). The * means gender differences.

When analysing the main effect of sex, male swimmers showed higher height, arm span, body mass, speed, SF, SI, drag, P_o, power per stroke, F_{max} and F_{mean}. Only in the four flexibility related variables, females presented greater values than males. Regarding skill level, experts registered higher speed, SF, SI and lower IVV.

The MLR significantly predicted performance for male young swimmers ($F_{(13, 22)}$ = 21.69, $p < 0.01$, R^2 = .97, adjusted R^2 = .92), with left shoulder flexion ($p < 0.01$), SI ($p < 0.01$), IdC ($p < 0.05$), P_o ($p < 0.05$) and F_{max} ($p < 0.05$) showing significant results. Regarding females, the same analysis was not statistically significant ($F_{(13, 25)}$ = 1.79, p = 0.17, R^2 = .65, adjusted R^2 = .28). Likewise, males showed direct relationship between speed and SI (r = 0.87, $P < 0.01$), IVV (r = -0.70, $P < 0.01$), height (r = 0.42, $P < 0.05$), SF (r = 0.45, $P < 0.05$), SL (r = 0.50, $P < 0.05$) and P_o (r = 0.45, $P < 0.05$) and females only registered with SF (r = 0.54, $P < 0.01$).

Discussion

The current study aimed to conduct an integrative analysis to understand the main sex and skill level effects in young swimmers performance. Differences between skill levels (speed, SF, SI and IVV) were registered, but the major dissimilarities were observed when reporting the main effect of sex (height, arm span, body mass, shoulder flexibility, speed, SF, SL, drag, P_o, power per stroke, F_{max} and F_{mean}). Although our swimmers have already finished their maturation process, they are still exploring different swimming solutions considering the distinct constraints that they have to face, thus, they do not have enough experience to be considered experts. This was expressed in the few variables that distinguished skill levels, being all of them biomechanical and the majority related to efficiency (SI and IVV). Additionally, males MLR highlighted shoulder flexion, SI and IdC as performance predictors, being the same model non-significant for females, corroborating the above mentioned that the “expert concept” should be carefully used in these ages, not existing an ideal solution that learners must imitate. Hence, results confirmed that boys clearly differentiate from girls after maturation.

The observed anthropometric sex differences corroborate literature, evidencing that several changes occurs during the maturational process and at its end clear differences are observed between sexes (Kojima, Jamison, & Stager, 2012). Although it is well known that men usually show lower flexibility due to a greater muscle stiffness, few swimming studies included that analysis. Nevertheless, in the current study females showed higher values in the four related variables, supporting other studies (e.g. Geladas, Nassis, & Pavlicevic, 2005). As in adults (e.g. Pelayo, Sidney, Kherif, Chollet, & Tourny, 1996) and in age-group studies in the same pace (Silva et al., 2014; Zamparo, 2006), a greater SL in males and lower SF in females, were observed. These could be due to the greater arm spam exhibited by males, although less expert females showed a greater SL value compared to their male counterparts and also expert females, confirming that the learning process was not finished yet.

The capability to produce high propulsive force, while minimizing the opposite drag, is decisive to achieve higher speeds (Toussaint et al., 2004). As drag increases with speed (e.g. Ribeiro et al., 2015) and denoting that male exhibited better anthropometric characteristics (drag influencing factors), the higher male drag comparing to female was explained. Conversely, the propulsive forces related parameters – P_o and work per stroke – were also higher in males, probably due to the fact that these coefficients were obtained from drag values. Propulsive forces have been considered highly dependent on strength (e.g. Geladas et al., 2005) and it is well known that men have a greater ability to produce force, mainly after the maturation process, corroborating our data that showed higher F_{max} and F_{mean} in males. In fact, it has been found that, in sprint races, speed is positively correlated to maximum or average force (Morouço, Marinho, Amaro, Pérez-Turpin, & Marques, 2012), explaining our male higher speed values. The strength importance have been also confirmed in a young swimmers longitudinal study that, with no drag differences, evidenced a 14% improvement in 100-m front crawl performance related to a higher maximal force (34%), speed (12%) and power (49%) measured on MAD-system (Toussaint, Delooze, Vanrossem, Leijdekkers, & Dignum, 1990).

When analysing the main skill level effect, the higher speed was based on higher SF, in both sexes, confirmed through the Pearson correlation. It corroborate with adult results that showed increasing SF, while rising speed (Chollet et al., 2000; Pelayo et al., 1996). However, the adult SF values were higher than those found in young swimmers, suggesting that although expert swimmers were faster, their learning process seemed unfinished, explaining the similarities in coordinative variables (CRP, SD of CRP, time spent in in-phase, anti-phase and out-of-phase). SI and IVV results denoted that faster swimmers are focused on achieving a better technique, since the latter has been used as swimming technique characterizer, being its value, as well as SI, considered swimming efficiency indicators (Vilas-Boas, Fernandes, & Barbosa, 2010).

Expert swimmers showed greater SI values when considering skill effect and this variable was also considered a performance (speed) predictor, but SI and speed are co-variants, explaining its significant effect. In males, IVV that is considered as important distinguishing variable on elite swimmers (Vilas-Boas et al., 2010), was not considered a significant performance predictor (although exhibited a direct correlation), confirming that in these ages, a considered “expert” could not be the fastest in the future. The negative IdC, which was also considered a performance predictor, was in accordance to literature in young swimmers (Silva et al., 2014), but in disagreement to elite swimmers results that adopt opposition or even superposition modes (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007). In fact, it has been argued that aerobic, anaerobic capacities and skill acquisition are affected by growth and development (e.g. Bar-Or, Unnithan, & Illescas, 1994), suggesting that performance factors are different in young vs. adults. Finally, the left shoulder flexion suggests a greater stiffness in that joint in less skilled. However, as only left shoulder was considered a predictor, and knowing that most of the swimmers were right-handed, it seems to suggest that each upper-limb performed different functions leading to different degrees of flexibility, nevertheless, more studies are needed in this topic.

For girls, the same model did not predict performance, denoting that after maturation, both sexes greatly differ and, also proposing that other variables should be considered when analysing young females in swimming performance. In fact, only SF showed to be positively correlated with speed in females, suggesting that this group is very homogeneous in the other variables, confirming that the “expert” concept in young swimmers is not suitable. In a 100-m front crawl study, boys aged 7 to 17 years showed to be greatly dependent on somatic traits, proposing that during growth, performance is mainly influenced by mechanical factors and less on relative aerobic and anaerobic capacities (Sprague, 1976). Nonetheless, that study was conducted only with boys, composed by a large age range and in the current study differences were clearly observed between sexes.

Conclusion

Sex has proved to be an important influencing factor in performance, suggesting that in the same task, coaches could give different feedbacks according to swimmers sex. At these ages, boys highlighted the most important variables to achieve better performances, denoting a possible underdevelopment technique in girls (they are younger). Moreover, this study also indicated that in these ages biomechanical variables play an important role, with swimmers focused on accomplishing a better and efficient technique (through better SI and IVV results). However, to better understand females sprint performance in these ages, more variables should be included in the analysis.

Disclosure statement

No potential conflict of interest was reported by authors.

Acknowledgments

This work was supported by Portuguese Science and Technology Foundation under Grant SFRH/BD/87780/2012.

Chapter 7.

The effect of a coordinative training in young swimmers performance

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Submitted on Journal of Motor Behaviour

Abstract

This study aimed to investigate the 8 weeks effects of a coordinative in-water swimming training. Twenty-six young swimmers (16 boys and 10 girls) were divided in two groups: the control and the training group. Swimmers performed 50-m sprint recorded by seven land plus six underwater Qualisys cameras. A linear mixed model regression was applied to investigate the training effect adjusted for gender. Differences were observed between moments in coordinative (time spent anti-phase, out-of-phase and pull phase) and performance variables (SF, SL, SI and IVV), and an interaction (group*time) was found in CRP, speed, SL and SI, leading to conclude that these sessions exerted a greater (indirect) influence on performance than in coordinative variables.

Keywords: Coordination, young swimmers, motor adaptability, ecological dynamics, biomechanics.

Introduction

Performance of locomotor tasks, such as walking, running, or swimming, requires the coordination of spatiotemporal patterns of upper and lower limb muscle activity (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006). Following the dynamical system approach, coordination will be the result of the interaction among three constraints (i) organismic (physical, psychological, morphological and physiological), (ii) task (specific to the task to perform and related to the goal and rules that governing the task), and (iii) environment (those that are external to the movement system as light, temperature or altitude) (Newell, 1986). Therefore, to achieve a certain goal or performance, a constant management of those constraints has to be carried out, as they limit the performers' action. Therefore, and within the ecological dynamics framework, there is no ideal motor coordination solution towards which all learners should aspire, but rather functional coordination patterns that arise from a self-organization (Davids, Button, & Bennett, 2008; Glazier & Davids, 2009; Newell, 1986).

During sport performance, if more functional movement patterns emerge as a result of movement variability due to the constant interacting constraints, a great movement exploration could be provided, allowing the performer to search for more varied and effective movement solutions to fit task dynamics (Davids, Araujo, Hristovski, & Chow, 2012; Davids, Araújo, Hristovski, Passos, & Chow, 2012). It has been argued that presenting the relevant constraints during the different skill development phases is the key for learners acquiring functional movement behaviour (Davids, Araujo, et al., 2012; Glazier, 2015). In fact, through the analysis of different sports (including sailing, basketball and boxing), it was observed that changes in behaviour raised during action (Araujo, Davids, & Hristovski, 2006), but fluctuations in the movement patterns themselves may or may not be functional (Davids, Araujo, et al., 2012), increasing the constant importance of manipulating constraints during the learning process.

In swimming, especially front crawl technique, different constraints have been analysed to understand how they influence coordination changes. Regarding environmental constraints, studies have been analysing different speeds (e.g. Chollet, Chalies, & Chatard, 2000; Seifert & Chollet, 2010; Seifert et al., 2015) and when using some equipment as paddles, swim suits and parachutes (e.g. Gourgoulis et al., 2009; Hue, Benavente, & Chollet, 2003; Telles, Barbosa, Campos, & Andries, 2011), meaning that swimmers have to face different drag magnitudes. Using task constraints, the influence of breathing action was studied (Lemaitre et al., 2009; Lerda & Cardelli, 2003; Lerda, Cardelli, & Chollet, 2001). However, it is with organismic constraints that more studies have been done, using characteristics or parameters related (directly or indirectly) to physical (stroke frequency and stroke length – e.g. Pelayo, Alberty, Sidney, Potdevin, & Dekerle, 2007; Potdevin, Bril, Sidney, & Pelayo, 2006), physiological (fatigue and energy cost – e.g. Figueiredo, Morais, Vilas-Boas, & Fernandes, 2013; Schnitzler, Brazier, Button, Seifert, & Chollet, 2011) and morphological (gender – e.g. Chollet et al., 2000; Seifert & Chollet, 2009) aspects.

In the above mentioned studies, only one conducted a longitudinal analysis, but with adult swimmers (Lemaitre et al., 2009), existing a lack of studies in young swimmers, who are still in the learning process. In fact, it was found that age changes the physical capacities and therefore the athletes' performance considerably (Dun, Fleisig, Loftice, Kingsley, & Andrews, 2007), and after the puberty period, slight coordination increases occurs (Hirtz & Starosta, 2002). Nevertheless, it still difficult to determine the best age for motor learning, but the predispositions seems best up to early adulthood (Hirtz & Starosta, 2002). To the best of the authors' knowledge, there is no interventional studies in young swimmers related to swimming coordination in front crawl technique. However, there are few on this topic trying to characterise young swimmers patterns analysing characteristics or variables related (directly or indirectly) to physical (stroke frequency and stroke length) and morphological (anthropometry, maturation and gender) aspects (Figueiredo, Silva, Sampaio, Vilas-Boas, & Fernandes, 2015; Silva et al., 2012; Silva et al., 2014).

In a continuous movement conducted only with fingers (e.g. Kelso, 1984) the authors observed that when movement frequency increases (and consequently speed), the coordination mode becomes unstable only to be replaced by another stable mode. In fact, this influence was also observed in adult studies when swimming front crawl, suggesting that speed and stroke frequency (SF) were the major influencing factors on changes in front crawl swimming coordination. Therefore, the aim of this study was to develop an 8 weeks coordinative training in young swimmers to investigate if more stable modes emerged at the fastest front crawl race (50-m). It was hypothesized that swimmers included in the coordinative trainings expressed a great coupled between arms after the intervention, comparing to control group.

Methods

Participants

Twenty-six young swimmers (16 boys and 10 girls), free from injury and with at least 6 times a week training, participated in the current study. Participants were divided in two groups: (i) the control group (CG) and (ii) in-water coordinative training group (TG). To be included in this study, swimmers should have participated in at least 70% of complementary training sessions (11 sessions) and in the two measuring moments. Following this, from the CG and TG 3 swimmers (3 boys) and 4 swimmers were excluded (3 boys and 1 girl), respectively. Table 1 shows the main physical and training background characteristics of each group separated by genders. The local ethics committee approved the procedures and all the swimmers' parents signed a consent form in which the protocol was explained. In addition, an maturation evaluation was accomplished, concluding that all swimmers were in the post pubertal maturational stage (stage 4 or higher; Tanner & Whitehouse, 1982).

Table 1. Swimmers age, height, body mass and training background per group.

	Control group (n = 11)	Training group (n = 8)
Age (years)	14.8 ± 0.9	14.8 ± 0.7
Height (cm)	166.6 ± 0.1	170.3 ± 0.1
Arm Span (cm)	167.1 ± 0.2	173.0 ± 0.1
Body mass (kg)	58.3 ± 10.1	58.1 ± 10.2
Practice (years)	5.5 ± 1.0	5.5 ± 0.9

Training Sessions

The CG only performed the normal training sessions in the swimming pool (without any complementary sessions). The TG performed twice a week during eight weeks (16 sessions) an additional coordinative training sessions in water.

In-water coordinative training sessions

Considering that speed and SF were the main front crawl swimming influencing factors (Chollet et al., 2000; Potdevin et al., 2006), it was used a task manipulation focusing on these two parameters. However, as the aim of the current study was also to understand the impact of coordination on performance the target of the in-water coordinative training was also the maximal speed. Therefore, following Navarro and Arsenio (1999), in each training session, it was developed training focused on maximal speed with 2 sets of 6 times 25 m. In each set, SF was manipulated in each repetition as follow: (i) preferred SF; (ii) slightly lower SF; (iii) greatly lower SF comparing to the preferred one; (iv) preferred SF; (v) slightly higher SF; (vi) greatly higher SF comparing to the preferred one. In each repetition the individual SF and the respective speed value was registered and a feedback was given to swimmers. The interval between each repetition was established at 1 minute and among sets was 3 minutes.

Test procedures

A standardized 1000 m warm-up at low to moderate swimming intensity was conducted in a 25 m indoor pool before experiments. Afterwards, each swimmer performed a self-paced 50 m front crawl at maximal speed, started in the water (without diving), with a non-breathing pattern in the centre of the pool to avoid start, turn and breathe effects on coordination. After each trial, participants were informed of their performance and if their time was not within ± 2.5% of their 50 m race time, he/ she repeated the trial.

Apparatus

While performing the 50 m front crawl test, swimmers used ten anatomical reflective landmarks in each body side (iliac crest, acromion, lateral humerus epicondyle, radius- and ulnar-styloid processes), enabling a 3D dual media working volume creation, where the orthogonal axes were defined as x, y and z for horizontal, medio-lateral and vertical (z = 0 defines the water surface) movements, respectively. A thirteen-camera setup (MoCap) was used, with seven land plus six underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 100 Hz. The calibrated volume was defined using underwater, above water and twin system to merge the first and the latter calibrations (according to the manufacturer's guidelines).

Biomechanical parameters

Swimming speed was assessed through the ratio of the hip displacement in an upper limb cycle (distance travelled between two consecutive entries of the same hand) to its total duration. SL was determined by the horizontal distance travelled by the hip during an upper limb cycle and SF was determined as the number of stroke cycles performed per minute. SI was computed by the product of speed and SL, and IVV was calculated through the ratio between speed standard deviation to mean speed.

Upper-limb coordination analysis

Coordination between right and left upper-limbs was assessed through the continuous relative phase (Hamill, Haddad, & McDermott, 2000; Lamb & Stöckl, 2014). CRP assessment between upper-limbs (arm-shoulder-trunk angle) was performed for two upper-limb cycles, recorded in the central part of the pool, with cycle duration expressed in percentage allowing its comparison. The CRP was calculated through the subtraction of the phase angle of the two oscillators at each point in time over the entire cycle (i.e. the left shoulder phase angles were subtracted from the right one). CRP values can range from 0º to 360º, but following Bardy, Oullier, Bootsma, and Stoffregen (2002), Diedrich and Warren (1995) and Seifert, Delignieres, Boulesteix, and Chollet (2007), a variation of ± 30° was accepted for the determination of a coordination pattern. Therefore, three different modes could be found: in-phase (when 330º < CRP < 30º), anti-phase (when 150º < CRP < 210º) and out-of-phase (when 30º < CRP < 150º and 210º < CRP < 330º). From that analysis, different parameters were extracted to examine the coordination between upper-limbs: (i) the mean CRP and its variability through the SD of CRP over a cycle; (ii) the relative time spent in in-phase, out-of-phase and in anti-phase (all expressed in %), to inform about the coupling between upper-limb coordination.

The relative time between two propulsive upper-limbs actions was also calculated, namely the index of coordination (IdC; Chollet et al., 2000), characterized as the time between the beginning of propulsion of the first right and the end of propulsion of the first left upper-limb cycles, and between the beginning of propulsion of the second left upper-limb cycle and the end of propulsion of the first right upper-limb cycle. IdC was calculated based on the division of the upper-limbs actions in four phases: (i) entry and catch, corresponding to the time since the entry of the hand in the water until it starts to make the backward movement; (ii) pull, since the end of the previous action until achieve the vertical alignment of the shoulder (first propulsive phase); (iii) push, since the end of the previous action to the exit the hand of the water (second propulsive phase) and (iv) recovery, covering the time from the exit of the hand until its new entry. The IdC and each stroke phase were expressed as the percentage of the duration of a complete upper-limb cycle; the sum of pull and push phases, and of catch and recovery phases, indicate the duration of propulsive and non-propulsive phases, respectively (Chollet et al., 2000). Three different synchronisation modes are possible to identify in front crawl: (i) opposition (IdC = 0%), when one upper-limb begins the propulsive phase and the other is finishing it, providing continuous motor action; (ii) catch-up (IdC < 0%), existing a lag time between propulsive phases of the two upper-limbs; and (iii) superposition (IdC > 0%), describing an overlap in the propulsive phases of both upper-limbs.

Statistical Analysis

All statistical analysis were conducted with Linear Mixed Models, a widely used method for longitudinal continuous data because it considers correlation between repeated measures and the maximum likelihood estimators are easily obtained using standard software (Laird & Ware, 1982). Changes in groups over time (group*time interaction) in coordinative variables – CRP, standard deviation of CRP, in-phase, anti-phase, out-of-phase, IdC, four upper limb phases (entry and catch, pull, push and recovery), propulsive and non-propulsive phases – and performance variables – speed, SF, SL, SI and IVV were modelled using a linear mixed-model regression with random-effects statements on intercept of each participant. Adjustments for gender were conducted in all variables analysed. The covariance type used for the random-effects was the variance components option. Normality of residuals was visually verified and data were expressed as mean ± SD. Vales of *P* less than 0.05 were considered significant and tests were two-sided, with statistical analysis performed using IBM SPSS software version 24.0 (SPSS, Chicago, USA)

Results

The effect of training on coordinative variables

The implemented coordinative training showed no influence on standard deviation of CRP, time percentage spent in in-phase, anti-phase and out-of-phase, IdC, time percentage spent in entry and catch and pull phases, SF and IVV. However, as presented in Tables 3, differences were noticed between groups in time spent in push, propulsive and non-propulsive phases (Models 9, 11 and 12, respectively). The time spent in push and recovery phases noticed differences from the pre- to the post-intervention (Models 9 and 10, respectively). Furthermore, a significant group*time interaction for CRP (Table 2 and Figure 3) was observed.

Table 2. Linear mixed model regression for continuous relative phase (CRP), standard deviation of continuous relative phase (SD of CRP), in-phase, anti-phase, out-of-phase adjusted for sex (Model 1 to 5, respectively).

			Slope (SE); statistical inference
CRP	Model 1	Group	-12.53 (5.92); p = 0.05
		Time	-1.14 (3.36); p = 0.74
		Group * Time	12.65 (5.18); p = 0.03
SD of CRP	Model 2	Group	-2.85 (7.74); p = 0.72
		Time	-1.26 (4.85); p = 0.80
		Group * Time	11.41 (7.47); p = 0.15
In-phase	Model 3	Group	1.40 (1.69); p = 0.42
		Time	-0.17 (1.01); p = 0.87
		Group * Time	-0.26 (1.56); p = 0.87
Anti-phase	Model 4	Group	-5.84 (5.71); p = 0.31
		Time	-7.17 (4.53); p = 0.13
		Group * Time	4.57 (6.97); p = 0.52
Out-of-phase	Model 5	Group	3.74 (5.60); p = 0.51
		Time	5.93 (4.69); p = 0.22
		Group * Time	-3.62 (7.22); p = 0.62

Table 3. Linear mixed model regression for index of coordination (IdC), entry and catch, pull, push, recovery, propulsive and non-propulsive phases adjusted for sex (Model 6 to 12, respectively).

			Slope (SE); statistical inference
IdC	Model 6	Group	-4.05 (2.13); p = 0.07
		Time	-1.70 (1.17); p = 0.16
		Group * Time	1.89 (1.80); p = 0.31
Entry and catch	Model 7	Group	4.46 (2.23); p = 0.05
		Time	-2.53 (2.04); p = 0.22
		Group * Time	-0.79 (3.15); p = 0.80
Pull	Model 8	Group	-2.32 (1.38); p = 0.10
		Time	2.21 (1.26); p = 0.09
		Group * Time	1.58 (1.95); p = 0.42
Push	Model 9	Group	-3.56 (1.58); p = 0.03
		Time	-4.87 (1.40); p = 0.00
		Group * Time	2.17 (2.16); p = 0.33
Recovery	Model 10	Group	1.15 (1.81); p = 0.53
		Time	5.64 (1.66); p = 0.00
		Group * Time	-3.42 (2.56); p = 0.19
Propulsive phase	Model 11	Group	-5.88 (2.13); p = 0.01
		Time	-2.66 (1.89); p = 0.18
		Group * Time	3.76 (2.91); p = 0.21
Non propulsive phase	Model 12	Group	5.61 (2.05); p = 0.01
		Time	2.38 (1.85); p = 0.22
		Group * Time	-3.48 (2.86); p = 0.24

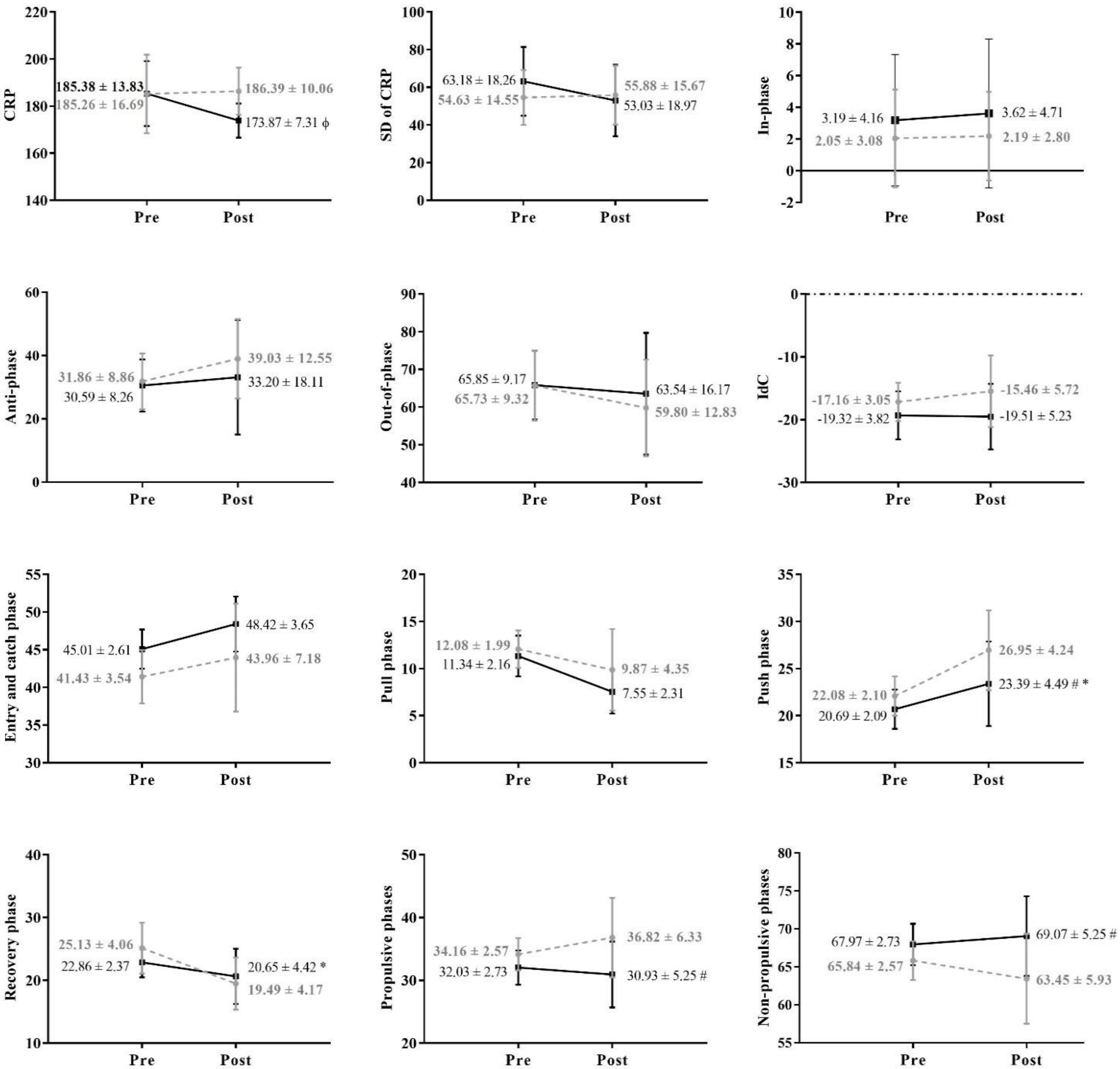

Figure 1. Pre and post-intervention comparisons for continuous relative phase (CRP), standard deviation of the continuous relative phase (SD of CRP), in-phase, anti-phase, out-of-phase, index of coordination (IdC) and the four upper-limb phases (entry and catch, pull, push and recovery phases). The grey and black lines represent control and training groups (respectively) and the symbols #, * and ϕ means that a group, time and an interaction time x group effects were found.

The effect of training on performance variables

As shown in Table 4 and Figure 2, a significant group*time interaction for speed, SL and SI (Table 4 and Figure 3) were detected.

Table 4. Linear mixed model regression for speed, stroke frequency (SF), stroke length (SL), stroke index (SI) and intracyclic velocity variations (IVV) adjusted for sex (Model 13 to 17, respectively).

			Slope (SE); statistical inference
Speed	Model 13	Group	0.65 (0.07); p = 0.36
		Time	0.02 (0.01); p = 0.05
		Group * Time	-0.05 (0.01); p = 0.00
SF	Model 14	Group	-0.75 (1.16); p = 0.53
		Time	0.95 (0.65); p = 0.16
		Group * Time	1.03 (1.00); p = 0.32
SL	Model 15	Group	0.11 (0.09); p = 0.24
		Time	-0.00 (0.02); p = 0.90
		Group * Time	-0.11 (0.03); p = 0.00
SI	Model 16	Group	0.28 (0.26); p = 0.30
		Time	0.03 (0.03); p = 0.41
		Group * Time	-0.28 (0.05); p = 0.00
IVV	Model 17	Group	-1.11 (2.64); p = 0.68
		Time	1.87 (1.30); p = 0.17
		Group * Time	2.28 (2.01); p = 0.27

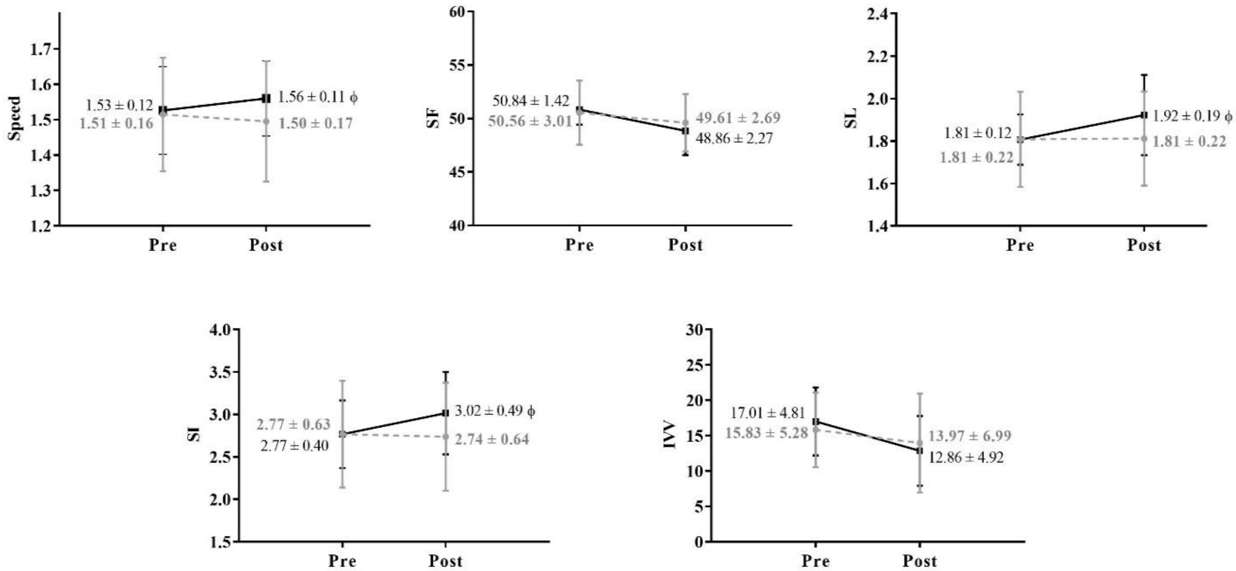

Figure 2. Pre and post-intervention comparisons for speed, stroke frequency (SF), stroke length (SL), stroke index (SI) and intra-cyclic velocity variations (IVV). The grey and black lines representing control and training groups (respectively) and the symbol ϕ means that an interaction time x group effect was found.

Discussion

The effect of training on coordinative variables

In the current study, two different methods were used to analyse front crawl swimming coordination, the CRP and its components (standard deviation of CRP, in-, anti- and out-of-phase) and IdC and its upper-limb phases (entry and catch, pull, push and recovery), with the first exhibiting information about space and time, and the latter only providing time information. Nevertheless, few differences between moments were noticed in both methods, with distinct behavioural tends. At the end of the intervention, CRP expressed a mean value related to an anti-phase mode in both groups (as the swimming technique demands), but the interaction found (group*time) denote that those groups developed different coordinative profiles as a result of the coordinative training conducted. Therefore, the training session developed influenced the coordination pattern adopted leading the swimmers of the TG to decrease the mean CRP.

The time spent in push and recovery phases were influenced by time, showing an increase in the former and a decrease in the latter in both groups. However, the TG showed smaller changes in the both phases, suggesting that their swimmers were trying to stabilize their coordinative pattern. In fact, although not significantly different, IdC in TG exhibited almost no change and the standard deviation of CRP showed tend to decrease its value in opposition to the CG. Considering that speed tend to rise in TG (as an interaction group*time was observed – Figure 2), these values seems to suggest that swimmers that participated in the intervention program, applied better their propulsive phases, although they showed lower results in the propulsive phases alone and, consequently, its sum. The higher SI registered by TG in the post-intervention seems to confirm that idea, since a high SI has been related to higher swimming efficiency (Vilas-Boas, Fernandes, & Barbosa, 2010). Conversely, the higher propulsive phases exhibited by CG could be a result of an inappropriate hand orientation (Seifert, 2010), leading them to spent more time in that upper-limb phase (as IdC only gives temporal information).

Following the ecological approach, a constraint-led perspective provides a search for functional coordination solutions that arise from the individual (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013; Newell, 1986), leading to discover preferred and typically stable coordination patterns (Hodges, Hayes, Horn, & Williams, 2005; Newell, 2003). Empirical evidences in sport showed that when informational task constraints are altered, different patterns tend to arise (Dicks, Button, & Davids, 2010), but it could occur a continued pattern improvement instead of an emergence of a new one (Newell, 2003). This could have happened in the current study, since our swimmers have already more than 5 years of practice. Thus, they could be between control or skill stage (Newell, 1986), where a stable coordinative front crawl pattern already exist. Notwithstanding, the training program implemented was not enough to change IdC toward the coordinative patterns adopted by adult swimmers that in the fastest races achieved IdC values closer or above zero (superposition only in men; Chollet et al., 2000; Potdevin et al., 2006).

Studies with young baseball (Chen, Liu, & Yang, 2016) and tennis (Huys, Smeeton, Hodges, Beek, & Williams, 2008) athletes, found that with similar coordination framework, the coordination differences among groups were found in the contents of relevant components and kinematic parameters, corroborating our findings. Based on non-linear dynamics, studies showed that when analyzing coordination changes, it must be considered the perturbation magnitude of the existing constraints, distinguishing low- and high-order parameters of behavior. The former are usually related to general biomechanical parameters (e.g., speed and SF), reflecting simple inherent mechanisms (i.e., over space or time) that lead to the emergence of behavior, and the latter, combine multiple lower-order parameters to capture the system coordination dynamics (Haddad, van Emmerik, Whittlesey, & Hamill, 2006). Therefore the locomotor system seems to use a rich repertoire of compensatory adjustments in response to the different task and environmental constraints (Chen et al., 2016; Haddad et al., 2006).

Furthermore, although not significant decreases in the standard deviation of CRP was observed, a trend to show different behaviour could be observed in the Figure 1, with the TG exhibiting a trend to decrease and CG to increase. In fact, the age of the sample could have influenced that result, since it is known that the movement variability follows the central nervous system development (Boyer, Silvernail, & Hamill, 2016; Denckla, 1974), showing a decrease through childhood and adolescence to adulthood (MacDonald, Nyberg, & Bäckman, 2006). This fact seems to explain why the standard deviation of CRP and IdC results did not alter significantly, suggesting that the coordinative pattern adopted by young swimmers also depend on their central nervous system maturation. Still, this training program seemed to enlarge the TG coordinative repertoire, as they increased (slightly) speed and SL and the propulsive upper-limb phases appears to be more efficient. Indeed, it was suggested that the lower range of swimming speeds during training and race, could result in a lower range of coordination repertoire, for instance, by long distance swimmers and triathletes (Millet, Chollet, Chalies, & Chatard, 2002; Seifert et al., 2010).

The effect of training on performance variables

Differences between pre- and post-intervention were noticed in SL, suggesting that TG showed technical improvements, as it is known that an improved swimming technique results in a longer SL, being this parameter more related to performance than SF (Millet et al., 2002; Pelayo, Sidney, Kherif, Chollet, & Tourny, 1996; Toussaint & Beek, 1992). Moreover, a SF minimization while increasing SL from the first to the second evaluation moment was noticed, a strategy used by elite swimmers to attain a more economical stroke pattern (Nikodelis, Kollias, & Hatzitaki, 2005; Pelayo et al., 1996). Considering that speed is the product of SL and SF (Craig & Pendergast, 1979), the greater SL increase in TG comparing with CG explains the trend to exhibit a superior speed by TG at the post-intervention. Following these changes, and confirming that a technical improvement occurred, SI (a considered swimming efficiency variable; Barbosa et al., 2010; Toussaint, 1992; Zamparo, Pendergast, Mollendorf, Termin, & Minetti, 2005) registered better results in the post-intervention. However, as in SL and speed values, this SI improvement (once it is the product of speed and SL) was mainly due to changes occurred in the TG, which obtained higher results in post-intervention.

The eight weeks training program coincided mainly with the specific preparation phase, which is generally characterized as a period of a volume and intensity training increases (Maglischo, 2003), leading to possible speed reductions (Olbrecht, 2000). In fact, a slight speed decline was noticed in CG, in opposition to the TG, which could be due to the fact that the training program chosen, was mainly targeted to speed development (Navarro & Arsenio, 1999). Therefore, the TG had an extra speed training sessions twice a week, which could have been enough to increase speed slightly. The SL and SI increases observed in TG explained that results in speed, showing that swimmers included in that group experienced greater technical improvements due to the specific coordinative training program. Indeed, upper-limb coordination is not only relevant to propulsive phases, but also to cover the buoyancy and breathing issues (Seifert, 2010).

In summary, this intervention allowed swimmers to experience different coordination modes (enlarge repertoire), leading them to change their pattern (CRP), but also led to performance improvements (speed, SL and SI) as a result of a specific swimming training (same competition conditions and speed was the training target). Finally, some considerations should be pointed: (i) considering that the literature stated that speed and SF were the most influencing factors on front crawl swimming coordination (Chollet et al., 2000; Potdevin et al., 2006), it could also be manipulated speed and not only SF, however, as we were analysing competitive swimmers and the target was also performance, it was always used maximal speed, excluding environmental oscillations (resulting from drag variations); (ii) possibly the reduced number of young swimmers that composed our sample could have influenced the current study results, however, considering that they are competitive swimmers, representing two well organized Portuguese swimming clubs, it seems that they clearly represent the young swimmers reality.

Chapter 8.

Are functional coordination and performance influenced by strength training?

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Submitted on International Journal of Sports Physiology and Performance

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Strength results in a combination of factors which can be broadly classified as central (related to coordination: motorneurons activity and the coordinated activation of other muscles required to stabilize the limb) or peripheral (the individual muscle, such as size and fibers arrangement). Therefore, coordination strongly influence strength production and, consequently, the movement performance. The current study aimed to investigate the effect of eight weeks of dry-land and in-water training sessions in young swimmers coordination and performance. The participants (16 boys and 17 girls) were divided in three groups: (i) control, (ii) dry-land and (iii) in-water strength training group. Apart from the regular training sessions, dry-land and in-water groups underwent eight weeks (twice a week) in a gym and in-water strength training, respectively. Each group performed in front crawl: (i) 50-m maximal speed; (ii) 30-s maximal effort in tethered swimming (iii) 25-m incremental speed bouts on the MAD-system, all in front crawl. Seven aerial and six underwater cameras were used to assess kinematics, with upper limb coordination computed through continuous relative phase and index of coordination methodologies. A linear mixed model was used to analyse each program influences. Data evidenced that these different strength training influenced different variables, with dry-land trainings showing more influence in swimming performance and in-water training presented more coordinative changes. Nevertheless, more studies in this topic are needed to clearly confirm that strength training allowed enhancements in front crawl performance.

Key words: Front crawl, strength training, young swimmers, coordination, performance.

Introduction

In repetitive movements such as walking, cycling or swimming, muscles are used dynamically with a variety of different combinations regarding force generation (Enders, Maurer, Baltich, & Nigg, 2013). Indeed, although a muscle fibre is innervated by a single motor neuron, each motor neuron innervates more than one muscle fibre. For instance, during cycling, whereas kinematics appear to be unaffected, kinetics change, affecting muscle activation patterns and their variability (Enders et al., 2013), with this latter being an important motor control inherent aspect, expressing how neuromuscular system is adapting to the required force output regarding sensory input (Madeleine, Mathiassen, & Arendt-Nielsen, 2008). Therefore, the nervous system has to continuously deal and master the numerous degrees of freedom, involving neural connections distributed among muscles.

It has been proposed that the central nervous system use low-dimensional modules composed by muscles activated in synchrony, called (synergies; Haken, 1983), acting as blocks and simplifying the movement construction. Thus, muscle synergies can be defined as a muscles unity organized to stabilize performance. However, despite the muscular action being functionally linked to brain and behavioural organization, it was suggested that it also follows general principles of complex dynamical systems, meaning that constraints (organismic, environment and task; cf. Newell, 1986) also reduce the redundant degrees of freedom. Therefore, the whole coordinated movement would result from several muscles interacting with each other as agonists, antagonists and synergists to complete a forceful movement without compromising balance and joint integrity. The timing and degree of activation of the involved muscles must therefore be controlled adequately, defining the whole movement coordination.

In cyclic sports, it is well known that a great spatio-temporal coordination of upper and lower-limbs muscle activity is required. Specifically in swimming, it has been shown that sprinting is highly influenced by a wide range of neuromuscular and biomechanical factors, such as muscle power, propelling efficiency and mechanical work (Toussaint & Truijens, 2006). It was stated that the ability to push a great water volume quickly (i.e. develop high propulsive forces) characterizes skilled performance (Counsilman, 1981), but no specific in-water strength training studies were conducted with young swimmers and only a few analysed dry-land strength training. Indeed, young swimmers interventional studies in this topic are reduced comparing to adults, and their conclusions did not clearly show that strength training allowed enhancements in performance, although a tendency to sprint improvements were noticed.

No performance enhancement was found after a dry-land strength training (Tanaka, Costill, Thomas, Fink, & Widrick, 1993), whereas combined swimming strength and swimming-specific in-water strength training increased speed (Toussaint & Vervoorn, 1990). In fact, to conduct a proper swimming strength training programs it should be considered: (i) swimmers are in prone position; (ii) both upper and lower-limbs are used actively for propulsion; (iii) water immersion leads to hydrostatic pressure and modifies respiratory timing; and (iv) apart from start and turns, swimmer’s movements are applied against deformable elements (Aspenes & Karlsen, 2012).

Swimmers age and their characteristics as growth and maturation have to be taken into consideration in the training specification, since it was reported that young swimmers increased their maximal swimming speed through a better force generating capacity (Toussaint, Delooze, Vanrossem, Leijdekkers, & Dignum, 1990) because of age-related increases in muscle size (Malina, Bouchard, Rocha, & de Mello, 2002). Furthermore, young swimmers have to deal with changes occurred during puberty, which could be related to neural function improvements, muscles stiffness increases and rises in hormones concentration (Malina et al., 2002). The current study aimed to examine the effect of eight week dry-land and in-water strength training program in young swimmers coordination and performance. It was hypothesized that in-water would enlarge more than dry-land strength training swimming coordination repertoire and performance, as it a more specific training.

Methods

Participants

Thirty-three age-group swimmers, free from injury, participated in this study (Table 1). Participants were divided in control (CG: 6 girls and 5 boys), dry-land (DLG: 5 girls and 7 boys) and in-water strength groups (IWG: 4 girls and 6 boys). The inclusion criterion was to have participated in 70% of strength training sessions (11 sessions). The local ethics committee approved the testing procedures and all swimmers parents signed a consent form in which the protocol was explained. A swimmer's maturation evaluation was accomplished, being all situated in post-pubertal stage (stage 4 or higher; Tanner & Whitehouse, 1982)

Table 1. Swimmers age, height, body mass and training background per group.

	Dry-land group (n = 12)	In-water group (n = 10)	Control group (n = 11)
Age (years)	14.8 ± 0.8	15.9 ± 0.9	14.8 ± 0.9
Height (cm)	168.2 ± 5.6	166.0 ± 8.3	166.6 ± 0.1
Arm Span (cm)	172.3 ± 6.9	170.7 ± 12.5	167.1 ± 0.2
Body mass (kg)	60.7 ± 9.3	56.3 ± 8.7	58.3 ± 10.1
Practice (years)	5.4 ± 1.9	6.7 ± 2.4	5.5 ± 1.0

Design

CG only performed the regular training sessions in the swimming pool (without any complementary sessions). During eight weeks, twice a week, DLG performed additional training sessions in the gym, in the pool facilities, before or after the swimming training. Based mainly on calisthenics exercises, it were also used elastic bands, medicinal ball, dumbbells, and swiss ball. Apart from preventing injuries, this program focused on speed development, therefore, swimmers were asked to perform fast movements. Four parts composed the training (Salo & Riewald, 2008): (i) 10-min warm-up including aerobic exercises; (ii) a circuit composed with seven exercises mainly focusing on the large muscle groups and multi-joints; (iii) three exercises of shoulder joint reinforcement; and (iv) 5-min dedicated to stretching. In the circuit three sets of 10 to 20 repetitions were performed in the dynamic movements and 30-s to 1-min duration in static exercises (as planks). The circuit was composed by plyometric exercises for lower (e.g. squats and long jumps varying from 60 to 100 foot contacts per session) and upper-limbs (medicine ball pitches), abdominal and low-back exercises and 30-s maximal speed on swim bench.

Focused on front crawl sprint, the IWG conducted an equal training frequency as DLG. The training focus was on upper-limbs strength, as most of front crawl propulsion is an upper-limb action result (Toussaint, Roos, & Kolmogorov, 2004). Therefore, in each session, swimmers were asked to perform 2 x (6 x 25 m) at maximal speed (Navarro & Arsenio, 1999), with half the sessions in the measuring active drag (MAD) system and the other half using hand paddles.

Methodology

A standardized 1000-m warm-up at low to moderate swimming intensity in a 25-m pool was accomplished. Afterwards, swimmers performed 50-m maximal test using ten anatomical reflective landmarks in each body side (iliac crest, acromion, lateral humerus epicondyle, radius- and ulnar-styloid processes) enabling the creation of 3D dual media volume, where the orthogonal axes were defined as x, y and z for horizontal, medio-lateral and vertical (z = 0 defines water surface) movements, respectively. A thirteen-camera setup (MoCap) was used, seven dry-land plus six underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 100 Hz. The calibrated volume was defined using underwater, above water and twin system to merge the first and the latter calibrations (according to the manufacturers guidelines).

Performance was determined by swimming speed that was computed as the ratio of the hip displacement (SL in $m \cdot cycle^{-1}$) in an upper-limb cycle (distance travelled between two consecutive entries of the same hand) to its total duration. Stroke frequency (SF in $cycles \cdot min^{-1}$) was determined as the number of upper-limb cycles performed per minute. Stroke index (SI in $m^2 \cdot s^{-1} \cdot cycle^{-1}$) was computed by the product of speed and SL. Intra-cyclic velocity variations (IVV) were calculated through the ratio between standard deviation of speed to the mean hip speed. To measure coordination two methods were used: (i) a temporal method, index of coordination (IdC), assessed following Chollet et al. (Chollet, Chalies, & Chatard, 2000), whom indicated that exists three different coordination modes: catch-up (IdC < 0), opposition (IdC = 0) and super-position (IdC > 0); (ii) a spatio-temporal method, continuous relative phase (CRP) that was calculated through the subtraction of the phase angle of the two oscillators at each point in time over the entire cycle (i.e. the left shoulder phase angles was subtracted from the right one), with three modes varying from 0 to 360º: in-phase (0º ± 30º), anti-phase (180º ± 30º) and out-of-phase (30º < CRP < 150º and 210º < CRP < 330º).

Each swimmer performed 30-s tethered test, with normal breathing, at maximal intensity using a belt attached to a 5-m length steel cable connected to a load-cell. With the cable fully extended, the test start and end were defined through an acoustic signal, with data collection starting when the first upper-limb cycle was completed to avoid the cable extension inertial effect usually observed immediately before or during the first upper-limb action. Force signal was acquired by an A/D converter (BIOPAC System, Inc., Goleta, CA, USA) at a 500 Hz sample rate and filtered with a low pass digital filter with a cut-off frequency of 10 Hz. The mean, maximal and minimum forces (using 30-s, the first 10-s and the last 5-s for F_{mean}, F_{max} and F_{min}, respectively) and fatigue index ((FI = [(Fmax - Fmin) / Fmax] * 100 Morouço, Vilas-Boas, & Fernandes, 2012)) were calculated.

To assess drag, swimmers performed 25-m at maximal speed on MAD-system using only upper-limbs (Toussaint et al., 2004). Assuming a constant swimming speed, the mean force equals to mean drag force and the ten speed/force ratio data were least square fitted according to $D = A \cdot v^n$, where D is active drag, *A* and *n* are parameters of the power function and *v* represents swimming speed (Toussaint et al., 2004). Mechanical power output ($P_o = D \cdot v$), work per stroke ($D \cdot SL$) and propelling efficiency ($e_p = A \cdot v^3_{free} / A \cdot v^3_{MAD}$) were also assessed.

Statistical analysis

Changes in groups over time (group*time interaction) in strength, coordinative, biomechanical variables were modelled using a linear mixed-model regression with random-effects statements on intercept of each participant. Adjustments for sex were conducted in all variables analysed. The covariance structure used for the random-effects was the variance components option. Normality of residuals was visually verified and data were expressed as mean ± SD. Statistical analysis was performed using IBM SPSS software version 24.0 (SPSS, Chicago, USA).

Results

DLG registered an interaction in F_{max} (ß: 43.74 ± 15.48, p = 0.01).

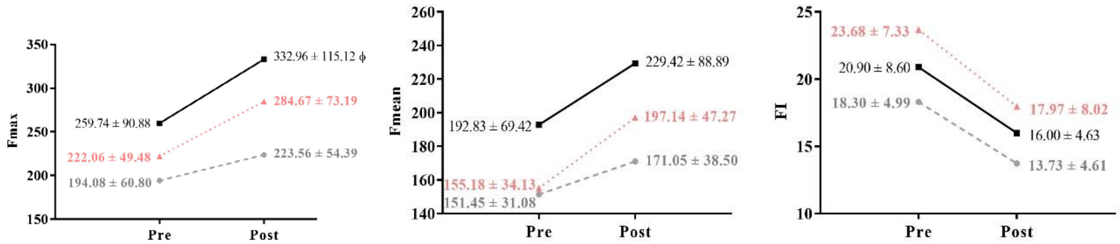

Figure 1. Pre- and post-intervention comparisons for maximal (F_{max}) and mean (F_{mean}) forces and fatigue index (FI). The grey, black and pink lines represent the control, dry-land and in-water training groups (respectively) and ϕ means that an interaction time x group effect was found with the control group.

At the end of the intervention differences between IWG and CG were noticed in CRP (ß: 31.89 ± 14.70, $p = 0.04$), with IWG showing a great decrease, and time spent in recovery phase (ß: -8.58 ± 3.88, $p = 0.04$), with CG registering a reduction in that phase. An interaction was found in time spent in push phase between CG and both training groups, with DLG (ß: -6.01 ± 1.74, $p < 0.01$) presenting a great increase and IWG (ß: -4.54 ± 1.83, $p = 0.02$) showing a more constant value. A similar pattern was observed in the time spent in recovery phase, but only with DLG (ß: 4.84 ± 2.15, $p = 0.03$) that slightly varied from pre to post-intervention in opposition to CG. Also, in CG and IWG (ß: -5.58 ± 1.93, $p < 0.01$), propulsive phases showed an interaction result.

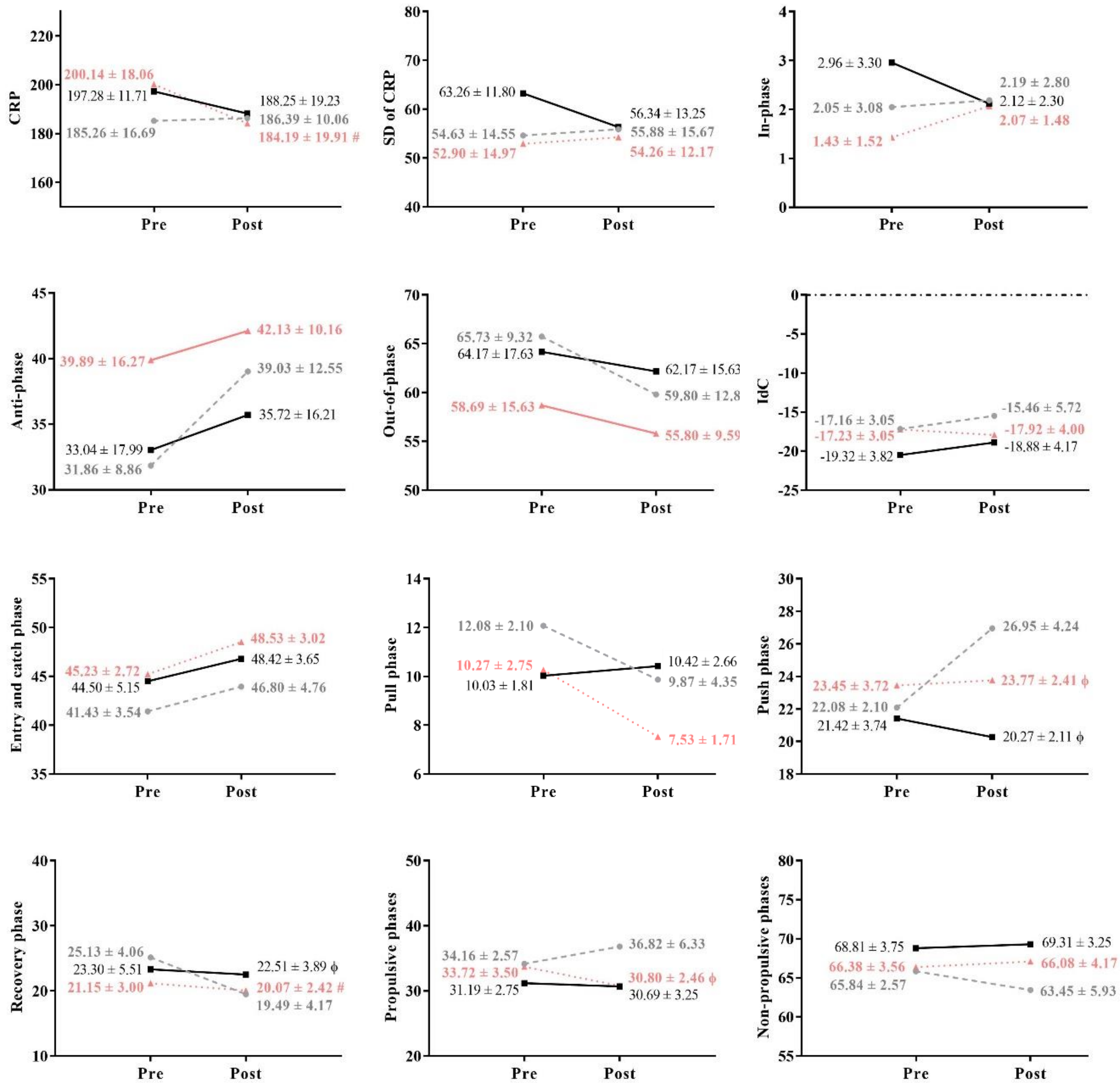

Figure 2. Pre- and post-intervention comparisons for continuous relative phase (CRP), standard deviation of the continuous relative phase (SD of CRP), in-phase, anti-phase, out-of-phase, index of coordination (IdC) and the four front crawl upper-limb phases (entry and catch, pull, push and recovery). The grey, black and pink lines represent the control, dry-land and in-water training groups (respectively) and # and ϕ mean that a club and an interaction time x group effect was found with the control group (respectively).

DLG registered an interactions with CG in speed (ß: 0.03 ± 0.01, p = 0.02), SL (ß: 0.07 ± 0.03, p = 0.02), SI (ß: 0.17 ± 0.06, p = 0.01), drag (ß: 18.67 ± 5.04, p < 0.01),

P_o (ß: 33.84 ± 8.68, $p < 0.01$) and work per stroke (ß: 42.94 ± 9.95, $p < 0.01$). Conversely, IWG group showed an interaction in speed (ß: 0.04 ± 0.01, $p = 0.02$).

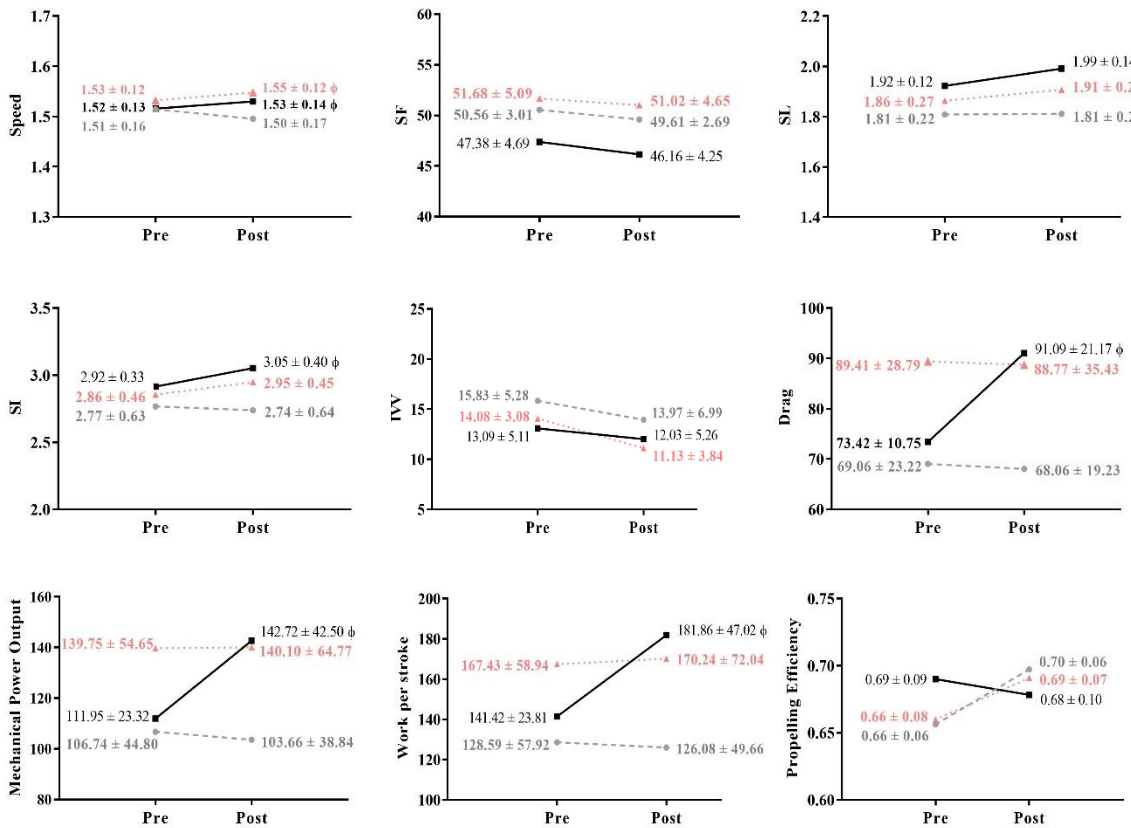

Figure 3. Pre- and post-intervention comparisons for speed, stroke frequency (SF), stroke length (SL), stroke index (SI), intra-cyclic velocity variation (IVV), hydrodynamic drag, mechanical power output, work per stroke and propelling efficiency. The grey, black and pink lines represent the control, dry-land and in-water training groups (respectively) and ϕ means that an interaction time x group effect was found with control group.

Discussion

The current study aimed to investigate the effect of eight weeks dry-land and in-water training sessions in young swimmers coordination and performance. The strength training implemented seemed to exert a different influence on included variables, with DLG exhibiting changes more related to performance and IWG to coordination.

Strength training is a common practice in most sports, aiming to enhance performance and/or prevent injuries. Strength and speed are described as the two major sprint performance influencing factors (Tanaka et al., 1993; Toussaint et al., 1990), being reported that the upper-body muscular strength and/or power output is highly correlated with speed in short swimming distances (r ~ 0.87 Toussaint et al., 1990). Nevertheless, it was shown that dry-land exercises do not electromyographically reflect neither the swimming effort nor the upper-limb coordination pattern (Olbrecht & Clarys, 1983), due to the fact that hydrodynamic resistance are impossible to reproduce in dry-land exercises, being the swimming features difficult to replicate on land (Tanaka et al., 1993). In the current study, although all groups increased both F_{max} and F_{mean}, only DLG stood out presenting an interaction result with CG. This could suggest that only dry-land training could improve strength, or may suggest that eight training weeks were not enough to produce observable differences in IWG.

The dry-land training conducted aimed to characterize the common strength training developed in the majority of swimming teams according to their material, space (gym), duration and exercises conditions with plyometric exercises. Based on swim specificities, the strength program aimed to mimic the in-water properties as much as possible. As the strength training focus was sprint races, swimmers were asked to perform fast, trying to stimulate their muscle power – which is the strength and speed combination. Muscle power stimulation seemed the most appropriated stimulus since it is directly related to swimming efficiency and to the ability to maximize propulsive forces by accelerating hands and upper-limbs through a cycle (Salo & Riewald, 2008). Hence, plyometric are training techniques used by athletes in all types of sports to increase strength and explosiveness, as it consists in a rapid muscle stretching (eccentric action) immediately followed by a concentric or shortening action of the same muscle and connective tissue. In fact, after puberty a strength consolidation is recommended through progressions to more advanced youth programs in resistance exercises, adding sport components and emphasizing exercise techniques (Kraemer & Fleck, 1993). However, to achieve this type of strength training with higher intensity, swimmers must have first to acquire the general basic techniques and methods, suggesting that its sessions should start at early ages.

Conversely, with the same environmental characteristics, IWG did not show significant differences in any strength variables between pre- and post-intervention, in opposition to what was observed in competitive swimmers that used MAD-system (Toussaint & Vervoorn, 1990). In that study, an older sample was analysed and the program lasted 10 weeks, during half an hour with a three time frequency, which could explain why at the end differences in strength and performance were noticed. Hence, in our program it was not possible to use MAD-system in every strength training session, being substituted by hand paddles. These hand enlargement is often used on swimming sessions aiming to increase upper-limb strength (Gourgoulis, Aggeloussis, Vezos, Antoniou, & Mavromatis, 2008), but in studies using different size paddles (Gourgoulis et al., 2008), it were only observed differences when using the biggest size (268 cm^2), suggesting that the small sizes were not enough to change the time spent in propulsive phases. Therefore, the load used in the present intervention could be not enough to achieve greater improvements, but considering the specificities of that training, some changes were possible to occur more related to coordination than to performance.

More changes in coordinative variables arose in IWG, corroborating our hypothesis. The CRP greatly decreased in IWG, in contrast to CG, although in the pre-intervention this variable expressed an anti-phase mode in all groups. In fact, front crawl swimming requires an anti-phase coordination pattern, as it is an alternated swimming technique, but in the pre-intervention, IWG presented the farthest value from 180º (the ideal anti-phase mode), reversing that result at the post-intervention. Following the dynamical systems approach, a key factor in understanding the skilled behavior emergence is based on constraints manipulation, i.e., the coach ability in structuring task constraints and organizing practice environments (Araújo, Davids, Bennett, Button, & Chapman, 2004). Regarding the task manipulation, it was suggested that the most significant constraint include the equipment nature used (Araújo et al., 2004), and considering that MAD-system in composed by fixed push-off pads with 1.35-m apart, this could led swimmers to a more symmetric movement, explaining those results. Also, the time spent in recovery phase showed a different behaviour in IWG and CG, with the first maintaining almost the same value and the latter reducing it. Nevertheless, at post-intervention, both groups showed similar results, although at the beginning CG exhibited a greater value, also explaining its trend to present higher IdC.

Data also showed an interaction between IWG and CG in the time spent in the push and propulsive phases, denoting the intervention effect. The former, maintained the time spent in push phase and decrease propulsive phases in opposition to CG that increased both phases. Those results could suggest that swimmers from CG greatly increased IdC and their propulsive ability. However, in the post-intervention, no differences were noticed in IdC, suggesting that IWG become more effective in power production in this phase, since this reduction did not reduce neither speed nor SL values. In fact these variables showed a trend to increase. In studies conducted with adults when using paddles, it was found a significant increase in the relative duration of push (Sidney, Paillette, Hespel, Chollet, & Pelayo, 2001) and pull phases (Stoner & Luedtke, 1979), leading to expect that a frequent training sessions with paddles would allow swimmers to maintain that pattern even without paddles. Other studies, did not found any modification in the relative duration of each upper-limb phase, but significant increases in the total duration of the underwater phases

(Payton & Lauder, 1995) or total cycle duration (Monteil & Rouard, 1992), were registered.

Although no dry-land programs in front crawl swimming were conducted aiming to observe the influence in coordination, it was expected that strength rises would allow increases in propulsive phases. DLG, the one that showed increases in strength, showed an interaction was also found in the time spent in push and recovery phases. As in IWG, those results suggest a better propulsive efficiency in DLG, as speed and SL followed the same pattern. Following this, IdC showed a trend to be more negative in the training groups, denoting a great catch-up mode, explaining the great time spent in out-of-phase instead of anti-phase mode. It was suggested that an individual power optimization is the key to achieve high speeds, since no correlation between IdC and propelling efficiency at maximal speed was found (Seifert et al., 2015). Furthermore, in age-group swimmers it has been reported that only catch-up coordination could be observed, since only elite male adult swimmers achieved IdC equal or above zero (opposition or super-position mode, respectively; e.g. Chollet et al., 2000), being this inability probably due to their slower swimming speed, as they do not reach the 1.8 $m \cdot s^{-1}$ threshold (Seifert, Chollet, & Bardy, 2004).

The eight-week training program coincided mainly with the specific preparation phase, which is commonly characterized as a period of volume and intensity training increases, leading to possible speed reductions (Olbrecht, 2000). In fact, the CG slightly decrease speed, showing a different profile when comparing to both training groups that increased speed. Also a different profile was found between CG and DLG in SL and SI, with CG exhibiting a constant SL and a slightly decrease in SI. Conversely, DLG showed an increase in both variables, explaining the trend to increase speed, as they are closely related (speed is the result of the product between SF and SL and SI results in the product of speed and SL).

A greater SF decrease in IWG was expected since as observed in a similar study with adult swimmers (Toussaint & Vervoorn, 1990). In fact, the expected increases in strength variables would be important to rise the propulsive impulse (the product of force and time), that have been considered a fundamental factor to attain high speeds in elite sprinting (Barden, Kell, & Kobsar, 2011). A study with faster runners showed that the ones that achieved higher sprint speeds, did it not because of an improved ability to move their legs faster, but because they increased the capacity to produce greater ground contact forces in a shorter period of time (Weyand, Sternlight, Bellizzi, & Wright, 2000). Nevertheless, all groups showed a trend to decreased SF while maintaining or increasing SL, suggesting that the propulsive impulse slightly enlarged.

These data seem to suggest that dry-land strength training is the most indicated strength program to increase front crawl swimming performance, since an interaction was found in speed and their co-variants (SL and SF) improved significantly. This profile is in agreement to those presented with elite performers that showed to be able to achieve longer SL while minimizing SF, resulting in a more economical stroke pattern. Hence, the SI value, which is an indicator of swimming efficiency, also increased in DLG, suggesting that improvements in swimming technique occurred. The registered drag rises in DLG could be explained by a better force-generating capacity due to an increased muscle size (Toussaint et al., 1990), also influencing P_o and work per stroke that are both drag dependent.

Practical Applications

Data showed that dry-land strength training should be included in the swimming programs to achieve better performances, especially when considering sprint races. Also, in-water strength should be also included for coordinative improvements. However, more studies are welcome in this topic, since data could not clearly state that strength training allowed an enhancement in front crawl performance, since at the end of the program few differences between groups were registered.

Conclusion

The main results suggested that dry-land training sessions improve front crawl swimming performance and, due to its specificity, the in-water training sessions are more related to coordinative modifications.

Acknowledgments

This investigation was supported by grants of the Portuguese Science and Technology Foundation (SFRH/BD/87780/2012). The authors would like to thank the coaches and swimmers that participated in the current study.

The individual intrinsic dynamics are unique, with the interacting constraints shaping performance and expertise acquisition (Davids, Button, & Bennett, 2008). In fact, previous experiments confirmed that different motor organizations could be observed to achieve an identical result (Hong & Newell, 2006; Rein, Davids, & Button, 2010). From this perspective, reaching perceptual-motor expertise no longer resides in acquiring a biomechanically ideal pattern, but rather in acquiring stable and flexible patterns, adaptable to the interacting constraints. Focusing on young swimmers, which are still in the learning process, the general purpose of the current Thesis was to understand the interaction between front crawl swimming coordination and performance. To achieve that aim we have identified the front crawl swimming coordination influencing factors (recognising its effects), understood behavioural flexibility when facing different task constraints, analysed the influence of gender and skill level on sprint performance and swimming coordination, and comprehended the effect of specific trainings on coordination and performance.

Swimming is a unique sport, where swimmers compete while suspended in a fluid environment, propelling themselves by pushing against liquid rather than solid substances. This create two major disadvantages compared to land sports as water offers less resistance to swimmers' propulsive efforts comparing to the ground that runners push against and considerably more resistance than air for swimmers progress forward (Maglischo, 1993). Considering those characteristics, it was accomplished an overview of the literature that examined front crawl swimming coordination, the fastest swimming technique with the higher range of race competitions and the most used on training (**Chapter 2**). In fact, studies in swimming coordination are relatively recent, but have started rising especially since the beginning of the 20th century.

In the above referred review it was highlighted that not all methods used to analyse coordination on land has been used in swimming with the same frequency, with the IdC being the most explored methodology. However, as this tool only characterizes time, disregarding another important component of coordination that is space, further studies using different methods to assess coordination are needed. It was also possible to notice that speed and SF have been considered the most coordination influencing factors, suggesting that these variables are the control parameters in front crawl swimming coordination. Moreover, no evidences have confirmed that a direct relationship between the coordination pattern adopted and skill level exists, mainly due to the lack of relationship between coordination and propulsion. Therefore, there is not an “ideal” coordination pattern to mimic and more studies are needed to understand the link between coordination and performance (particularly in young swimmers).

During the learning process, individuals are engaged in a progress towards a state of expertise, developing the capability to generate different types of functional performance solutions. This leads to an enlargement in their intrinsic dynamics (Phillips, Davids, Renshaw, & Portus, 2012), due to compensatory strategies that induce a reorganization of the movement structure (Pupo, Dias, Gheller, Detanico, & Santos, 2013). Therefore, during motor skill acquisition, coordination pattern variability plays a functional role in encouraging learners to explore the relationship between spatial-temporal parameters and the interacting constraints (Seifert et al., 2014). From a dynamical systems perspective, it has been suggested that coordination variability in a system provides the required flexibility to adapt to perturbations (Hamill, van Emmerik, Heiderscheit, & Li, 1999). However, it is known that within a given constraints there are typically a limited number of stable solutions that achieve the desired outcome (Warren, 2006).

Indeed, we have noticed that not all the variability is functional (**Chapter 3**), i.e., behaviour variability did not always correspond to functional adaptation, but is necessary to explore new possibilities (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013). However, the different six clusters found showed that movement variability might play an important role during learning, since it can reflect adaptive flexibility to task constraints. From the individual's point of view, the task diversification is a way to exploit physical and informational constraints to stabilize the intended behaviour (Warren, 2006). The patterns nature, as well as switching appropriately between those patterns (flexibility according to speed and stroke frequency), seems to be more important than getting the highest number of switching or patterns (range of repertoire). Indeed, although with increasing experience more stable patterns raises (reflecting a more economical organization mode; Sparrow & Newell, 1998), stability and flexibility should not be considered opposing concepts. In other words, flexibility increases is not a synonymous of stability losses, rather it reflects adaptability (Davids, Araújo, Hristovski, Passos, & Chow, 2012; Seifert, Komar, Araújo, & Davids, 2016).

Swimmers different behaviour flexibility described in the previous referred study confirm that the most adaptable performer (i.e., the expert) is the one that shows a better capacity to functionally interact with key constraints (the organismic, task and environmental; Newell, 1986), exploiting them to successfully achieve performance goals (Davids et al., 2013). Thus, sports expertise is not expressed by the capacity to repeat an idealized movement pattern in an identical way from trial to trial, but rather by the achievement of functional coordination solutions in dynamic performance environments (Davids, Araújo, Seifert, & Orth, 2015). Therefore, it could be argued that, from a dynamical systems perspective, a major reason why biomechanicists have been unable to identify the complete optimal solution for a given motor activity is that mathematical neuromusculoskeletal models currently do not consider the full range and uniqueness of constraints acting on each individual (Glazier & Davids, 2009). Moreover, the interaction between training and growth should be a central concern while assessing the individual pathway to expertise (Moreira et al., 2014).

Considering that it was highlighted that speed and SF are the most front crawl swimming coordination influencing factors (**Chapter 2**) and the literature (e.g. Kelso, 1984), and considering that SF is a covariant of speed, led to speculate if only one of these variables are really the control parameter of swimming coordination or if it is the combination of both. In fact, increases in swim speed lead to rises in SF, which is mainly accompanied by IdC increments (being this latter directly related with speed). This analysis was later accomplished by us (**Chapter 4**), being concluded that speed is the main control parameter on front crawl swimming coordination (at least at the studied speed and SF ranges), suggesting that to enlarge swimmers repertoire, they should focus more in speed manipulation rather than SF. Nevertheless, swimmers ages should be taken into account, since they are in the middle of training process, suggesting that the requested SF increases led swimmers to perform an improper hand path.

Complementarily, the multi-analysis of female age group swimmers performance accomplished allowed to understand if two different female skill levels registered as important different variables to explain their performance (**Chapter 5**). Surprisingly, anthropometric characteristics did not differ between skill level groups, in opposition to previous findings (e.g. Saavedra, Escalante, & Rodriguez, 2010; Tella, Llana, Madera, & Navarro, 2002), with these variables often considered discriminant factors between age group swimmers. Conversely, differences were observed between performance levels, with faster girls exhibiting greater SL, SI, F_{mean}, F_{max} and shoulder flexion values, better hydrodynamic profile, but lower IdC values. With the exception of the latter variable, all the others were in accordance to results obtained in adult swimmers (e.g. Pelayo, Sidney, Kherif, Chollet, & Tourny, 1996; Seifert, Chollet, & Rouard, 2007). In fact, IdC values presented an unexpected result, as in adults, the greater the swim level, the higher is the IdC value (e.g. Chollet, Chalies, & Chatard, 2000; Seifert & Chollet, 2008).

Based on the above referred results, a more broadly analysis was conducted to better understand young swimmers performance (**Chapter 6**). Twenty nine swimmers were split in two skill levels and sex groups, since at the end of maturation phase clear differences were observed between male and female swimmers (Kojima, Jamison, & Stager, 2012). In fact, our findings corroborated the literature, being observed several sex differences (height, arm span, body mass, shoulder flexibility, speed, SF, SL, drag, P_o, power per stroke, F_{max} and F_{mean}), in opposition to the lower dissimilarities observed between skill levels (speed, SF, SI and IVV). Although swimmers maturation process has already finished, swimmers seemed to continue exploring different swimming solutions considering the distinct constraints they have to face, not disposing enough experience to be considered experts. Therefore, the term "expert" should be carefully used at these ages, as the distinction between "less" and "more" experts implies that development can involve both qualitative shifts and stabilizations in knowledge and performance (Hoffman, 1998). This was reflected in the few variables that distinguished skill levels, being all of them biomechanical and the majority related to efficiency (SI and IVV).

In addition, in the same study (**Chapter 6**), the performance predictors in male swimmers were shoulder flexion, SI and IdC, but this model was non-significant for female swimmers. In fact, girls only showed a direct relationship between performance (speed) and SF, while boys noticed with SF, height, SL, SI and P_o, and an indirect relationship with IVV. Considering the conclusions observed in **Chapter 5**, these results in females were not expected, clearly suggesting that variability exists between swimmers (at least in age group female swimmers, since those studies were conducted with different female participants with the same age). Therefore, results seems to emphasize the above mentioned that the expert concept should be carefully used in youth, not existing an ideal solution that learners must imitate. Also, it was confirmed that boys clearly differentiate from girls after maturation, with the latter exhibiting a different swimming solution, with their main performance predictors out of those used in **Chapter 6**. Therefore, it was advised that, during training sessions, coaches should provide swimmers different feedbacks regarding swimmers sex.

To better understand the link between front crawl swimming coordination and performance, training sessions based on task constraint manipulation (speed and SF – the most influencing coordination variables, cf. **Chapter 2**) were accomplished. For that purpose, an eight week training program, with training sessions twice a week, was conducted with young swimmers. It was investigated the effects of specific coordinative in-water training, by comparing swimmers coordinative and performance results with a control group (**Chapter 7**). This last group only performed the regular training sessions with similar characteristics (intensity, volume and frequency) to the coordinative training group. Two methods to analyse swimming coordination measured: the IdC (as observed in **Chapter 2**) and the CRP (to have temporal and spatial information). At the end of this intervention program, differences were registered when comparing groups, but significant interactions in coordinative (CRP) and performance (speed, SL and SI) variables were disclosed.

In other sports, it was observed that with similar coordination framework, the differences among skill levels were found in the contents of relevant components and kinematic parameters (Chen, Liu, & Yang, 2016; Huys, Smeeton, Hodges, Beek, & Williams, 2008). In this case, only low-order parameters (mechanical modifications as general biomechanical parameters) changed, with the perturbation not being enough to exert changes in the high-order parameter (combination of multiple low-order parameters as coordination dynamics; Haddad, van Emmerik, Whittlesey, & Hamill, 2006). Following that, it seems that the locomotor system use a rich repertoire of compensatory adjustments in response to different task and environmental constraints (Chen et al., 2016; Haddad et al., 2006).

Knowing that strength is considered a key component in many sports, influencing abilities as power output, reaction time and agility (Young, 2006), its inclusion on training programs has also the important function of injury prevention (Cameron, Adams, & Maher, 2003), with swimming being no exception. However, considering that the traditional environment for strength training is not in-water, some concerns when planning a strength development program for swimmers have to be considered, since the hydrodynamic drag effect is impossible to be replicated on land (Maglischo, 2003; Sadowski, Mastalerz, Gromisz, & Niźnikowski, 2012). Indeed, coordinative structures or functional muscle synergies are dependent not only on processes of self-organization, but also in constraints imposed on specific neuromusculoskeletal system, as the environmental ones (Kugler, Kelso, & Turvey, 1980; Newell, 1986). The synergistic action of the muscles coordinating movements is reflected by the redundancy/abundancy in the available mechanical degree of freedom, which is usually associated with variability in relation to neuromuscular control (Latash, Scholz, Danion, & Schöner, 2001; Turvey, 1990). In fact, muscles coordinate human motions because the forces generated by them develop mechanical energy and mechanisms for energy exchange among segments (Zajac, 2002).

Considering the above mentioned, it was conducted a study to understand the effect of eight weeks of two different types of strength training on swimming coordination and performance. Thirty three young swimmers were divided in a control group (only performing normal swimming training),and two experimental groups that, in addition to their swimming training routine, performed dry-land and in-water strength training, respectively (**Chapter 8**). The main results suggested that dry-land strength training sessions are more related to front crawl swimming performance improvements and, due to its specificity, the in-water training sessions are more related to coordinative modifications. However, data could not clearly state that strength training allowed an enhancement in front crawl performance, since at the end of the program a few variables showed differences between groups were registered.

Swimming performance involves muscles activation organization to accomplish a certain goal, being that required organization the heart of coordination (Magill, 2011). However, coordination did not show a direct relationship with young swimmers performance, since these young swimmers always exhibited catch-up coordination mode with different swim performances, independently of their skill level. This seems to be due to the fact that coordination is a broad concept that depend on constraints acting on swimmer (Newell, 1986) that will shape the overall swimming performance. Nevertheless, swimmers should explore their capabilities through task manipulation (as speed and SF) to enlarge their repertoire, leading to better performances, since they will develop the capability to functionally adapt to the different constraints. The development of strength also influence both swimming coordination and performance capabilities, but with different magnitudes, as dry-land conditioning is more related to swimming performance improvements and, due to its specificity, in-water strength training is more close to coordinative modifications.

Chapter 10. Conclusions

Based on finding obtained in the experimental moments described in this Thesis, it is pertinent to stress out the following conclusions:

(i) Research in swimming coordination greatly increased in the beginning of the 20th century, with the IdC being the most used methodology to characterize coordination;

(ii) Speed and SF are considered to be the most influencing factor on swimming coordination, with speed exerting a preponderant effect;

(iii) There is no “ideal” of coordination pattern to mimic, the pattern adopted by swimmers emerge through the interacting constraints that act on in each swimmer;

(iv) The manipulation of task constraints showed that more important than change among many coordination patterns, shifting among the most appropriate swimming coordination pattern would lead to a better adaptability;

(v) In age group swimmers, the difference between skill levels it is not very clear, existing more differences between genders rather than skill level, at the end of the maturation process;

(vi) Coaches should be aware of the gender differences and give different feedbacks according to that;

(vii) Specific coordinative in-water trainings could lead to changes in front crawl swimming coordination, but also in its performance;

(viii) It was not clear if strength training exert an important improvement in swimming, but it seemed that specific strength trainings (in water) could be related more to changes in swimming coordination and dry-land strength trainings seemed to be more related to swimming performances improvements.

Chapter 11. Suggestions for Future Research

The present thesis aimed to enlarge the knowledge related to coordination, especially in front crawl swimming coordination. In fact, this topic have been poorly explored, namely in young swimmers that are still in the learning process. Therefore, there is a lack research regarding this issue. Thus, it is our purpose to continuous study deeply particularly following these ideas:

(i) As it is difficult to have many arm cycles in swimming (due to the short space capacity to capture swimming movement), it should be analysed the intra-individual cyclic variability in young swimmers using tethered swimming;

(ii) Extend the swimming coordination analysis to other swimming techniques;

(iii) Extend the coordination analysis to the arm leg coordination;

(iv) Deepen the coordination analysis to the intra-muscle coordination, trying to understand if muscle synergies and degeneracy really exists;

(v) In a continuous movement (large range of swimming cycles), investigate whether energy resources, i.e. the effect of fatigue, are the a influencing factor of coordination pattern changes;

(vi) Analyse if there are more movement variability when fatigue starts to rise;

(vii) Develop an strength training program based essentially on plyometric exercises and observe their main changes in coordination and swimming performance;

(viii) Understand if the preferred stroke frequency is the more economical swimming pattern as stated in running;

(ix) Examine if expert swimmers are able to show a multi-stable coordination when manipulating constraints, in opposition to non-expert swimmers that could not change among different coordination patterns;

(x) Explore the manipulation constraints to understand their influence in coordination and performance, but also to understand if a non-linear learning increase the coordination pattern repertoire.

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Chapter 1

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